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Design recommendations for multi-storey and underground car parks

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Contents

Glossary

Accessway	Carriageway not adjoining bays and used solely for the movement of vehicles.
Aisle	An accessway serving adjoining bays.
Bay	The parking area, exclusive of aisle or other adjoining area, allocated to one car.
Bin	Two rows of bays with the access aisle running between them. A half-bin is one row of bays and the aisle serving them.
Clearway ramp	A ramp system that does not include an aisle in its circulation and which provides unencumbered access between the parking floors and an entrance or exit.
Deck	A slab at any level of the car park.
Dynamic capacity	This term may be applied either to the individual parts of a car park or to a car park as a whole. It is the maximum flow per hour of cars, or where appropriate, people, which the part of the car park or the car park as a whole, as the case may be, can accommodate.
Parking angle	The angle between the longitudinal centreline of a bay and the aisle from which it is served.
Ramp	An accessway or aisle connecting parking areas at different levels. More usually, the term is applied to accessways only.
Reservoir	An accessway where cars may queue without obstructing movements in other parts of a car park or the external road system. A reservoir may also be described as a vehicle reservoir.
Static capacity	The total number of bays in a car park.

The first edition of the car park design guidance document was prepared in the late 1970s and updated in 1984. In the intervening years, the perception and design features of multi-storey car parks have changed significantly. The growth of car usage and increased familiarity with different multi-storey car park facilities has led to increased public expectations on issues such as security and ease of access. There has also been interest in upgrading provisions for car parking as a marketable facility. Increasingly, car parks are recognised as an integral and vital part of a development, often forming the first impression a visitor has of a town or specific development.

Many car parks designed in the 1960s and 1970s continue to give satisfactory levels of service and structural performance. However, some failures were reported in the mid-1990s, which mainly involved the older stock of car park structures. Among these incidents was failure of car park barriers caused by accidental impact that resulted in cars falling onto the lower floors. There were other well publicised failures, one caused by concrete degradation with reinforcement corrosion in a slab, the structural consequences of which were not appreciated before a punching shear failure initiated a partial progressive collapse. In recognition of the development of car park technology and to allow the lessons learnt from such failures to be incorporated into design guidance, the current review of Institution guidance was begun in July 1999.

The review noted that failures in older car parks frequently related to inadequate design details and insufficient understanding of the exposure conditions to which the structures could be subjected. Moreover, the performance of drainage and waterproofing, which are vital for durability of the floors, was found to be inadequate, whether as a result of bad detailing or insufficient quality control during construction. The situation was worsened by the absence of proper monitoring and maintenance. Regular and timely monitoring, inspection and maintenance of car parks by staff experienced in the particular mechanisms of corrosion and structural deterioration were also seen as important. The nature and mechanisms of certain forms of collapse give little prior warning of structural distress to the inexperienced eye. Failure to detect these mechanisms can allow concrete degradation and corrosion to progress largely unnoticed until structural collapse occurs. As with any structure, design details that enhance durability, facilitate proper inspection and the maintenance of drainage and waterproofing will significantly extend the life and security of a car park structure.

Historically, car parks have been designed according to guidance applicable for buildings. The review suggests that durability requirements, even for closed car parks, may be akin to those for bridges or marine structures, as a result of the de-icing salts either used directly or imported on the vehicle wheels. The review has highlighted that the following provisions significantly improve performance and durability of car parks in such locations:

- measures to prevent the ingress of chlorides into key structural areas
- positive and effective drainage systems that are easily accessed for maintenance
- detailing and specification to enhance durability
- details to prevent cracking and ingress of moisture into the structure
- a heightened understanding of maintenance requirements and the serious and expensive consequences of neglect.

To undertake a meaningful review of design guidance requires inputs by professionals from a wide range of backgrounds. For the review to be successful and authoritative, the review team must have expertise, understanding, interest and experience of details of car park designs that result in safe and durable structures. My thanks go to the whole task group who demonstrably fulfil the above criteria and whose expertise I have been privileged to observe. The new document is indebted to their willing contributions and openness in sharing experience gained over many years. I am particularly appreciative of the resolve of the task group and editing panel to prepare a document that addresses the important design issues in a practical way.

As with any design, arriving at recommendations mean that several different ways of achieving the same objective have to be considered and reconciled. I am pleased to say that the task group always managed to resolve any differences in a thoroughly professional manner. The support of the Institution secretariat has been much appreciated in enabling this process of, at times, abstract discussions of diverse aspects to be resolved into a coherent document for final agreement.

The current document represents the conclusion of over two years involvement for the task group. This period has been necessary to ensure that appropriate consultation was possible outside of the task group. My thanks go to all those who took the time to respond to drafts and raise points of concern from a wide range of perspectives.

The task group recognised at an early stage that future developments will always happen and this in turn will require the guidance to be reviewed and updated. For this reason we have tried not to be too prescriptive or suggest particular solutions. The lessons learnt from previous designs and failures of certain aspects have been taken into account and reflected in the guidance now provided. Use of these guidelines will assist with the creation of safe, durable and successful car park structures that provide long-term good value and performance for both the developer and the public user alike.

Jolyon Kenward
Task Group Chairman

Fig. 1.1 The Genesis multi-storey car park,World Cargo Centre, Heathrow

Fig. 1.2 Kuala Lumpur airport car park

1.1 General

Since the 1960s, car parking has become a major user of developable land. Multi-storey car parks, underground or basement car parks, and car parks in a multi-function building are common. Often, visitors gain their first impressions of a town from its car park, as this may be the first building with which they come into contact. The inferences are obvious. Although multi-storey car parks are mainly found in city and town centres, they also feature in airports, retail centres, conference centres, hotels, housing developments, places of employment (both offices and factories), places of entertainment, railway stations, and sports facilities.

Certain features are common to all of these and essential if the car park is to fulfil its function. Potential users should be able readily to identify a car-parking facility and its entrance. In urban areas, it helps if a public multi-storey car park can be easily recognised for what it is. Such car parks are usually open structures to permit natural ventilation and no higher than about 15m. Their main structural lines are typically near horizontal and, to meet circulation requirements, they may have external ramps.

A free-standing multi-storey car park (see Figs. 1.1 and 1.2) is essentially a functional building generally composed of a series of floors supported on columns to provide large areas of uninterrupted floor space. Therefore engineering considerations tend to be the primary driver for the solutions, rather than appearance. Little weather protection is required, and there is generally no need to roof over the top floor. Coupled with the wear from traffic and attack from de-icing salts, this lack of weather protection can lead to severe exposure conditions inside the car park, which must be borne in mind when detailing car parks. Often the emphasis is on achieving a low cost per car space, which leads to demands for a very economic building. If exterior ramps are called for, these considerably restrict design and appearance. The combination of these factors means that designing and constructing attractive multi-storey car parks is almost always a challenging task.

Where a car park is required as part of a development (see Figs. 1.3, 1.4, 1.5 and 1.6), it is usually better to integrate its design into the development as a whole. There may then be the option of designing the car park as a component part of a multi-function building or as a separate structure integrated into the development. For large developments, and when all costs are taken into account, there is no evidence that incorporating car parks in buildings with other functions

Fig. 1.3 Bluewater shopping centre car park

Fig. 1.4 Liffey valley shopping centre, Dublin

Fig. 1.5 Oracle shopping centre, Reading

significantly affects the cost of accommodating cars.

It may sometimes be desirable to site car parks underground (see Figs. 1.7, 1.8 and 1.9). However, these have specific environmental and design constraints and will normally require forced ventilation. The main plant intakes and exhaust ducts for fire protection and ventilation systems need to be carefully sited to avoid the impact of pollution from car fumes, smoke and noise. Siting car parks above ground usually reduces the cost of the structure and permits natural ventilation.

Complex issues arise when integrating a multi-storey car park among buildings of historic interest (see Fig. 1.10). Such car parks are usually built to an entirely different scale and may have little in common with the unit – the motorcar – for which the multi-storey car park is designed. In such circumstances, a strong case can often be made for using underground car parks instead of a multi-storey car park. If multi-storey car parks must be provided, they can, with advantage, be small, even though this may result in a greater number of individual car parks than would be considered economical or desirable. It is tempting to say that multi-storey car parks should be harmonised with their surrounding buildings, but this can rarely be done intimately, if only because much of the elevation is often required to remain open to satisfy fire and ventilation requirements.

1.2 Scope of the report

This report is intended for use by structural engineers who have an appreciation of the design process for buildings. Although these guidelines are intended for structural engineers, some sections include notes that are appropriate to other construction professionals and car park owners/operators.

The scope primarily relates to multi-storey car parks above and below ground, for access and use by the public. Single or ground-level car parks, car parks using mechanical stacking systems and small private access car parks – where different operational requirements and standards may be considered acceptable – are not specifically covered. Nevertheless, some of the design guidance here may be considered relevant to such car parks but may need modifying to suit the specialist requirements of their operation and constraints of space.

The form and order of the report has been established to provide chapters relating to key areas of design considerations in increasing detail, reflecting the typical

Fig. 1.6 Car park under construction for Mass Transit Railway Hong Kong

Fig. 1.7 Colon underground car park, Madrid, showing variety of landscaping above car park

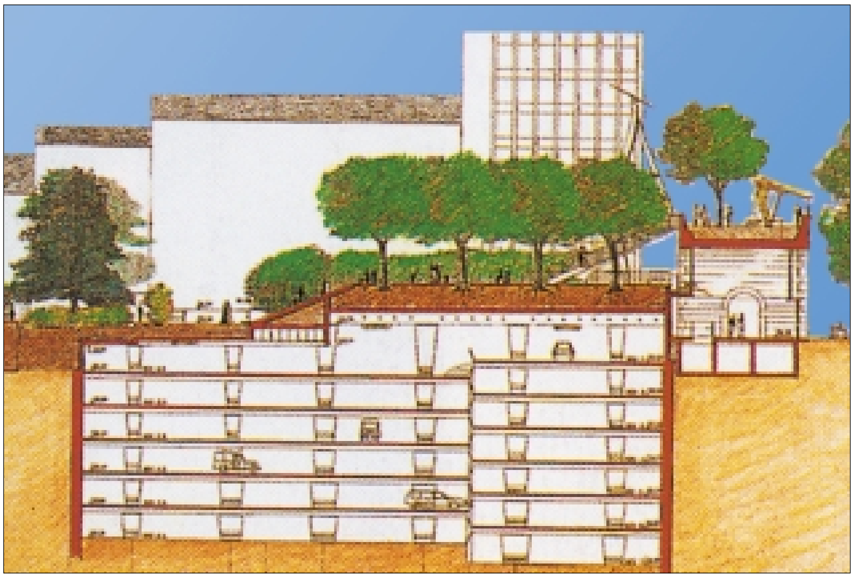

Fig. 1.8 Parc Hector Malot, Paris. Buried car park, showing landscaping

Fig. 1.9 A hillside car park in Seattle

Fig. 1.10 Underground car park close to buildings of historic interest

considerations at various stages of design development. The three main stages and grouping of chapters are:

- Agreement of the design scope and considerations necessary for general car park layout design and planning (Chapters 1–3)
- Structural considerations and issues related to the development of the structural form, framing and use of space (Chapters 4–7)
- Design details and specific measures that can be used to enhance durability (Chapters 8–11).

This report complements existing Standards and Codes of Practice by offering design guidance that is specific to car park design and construction. It is not intended as a stand-alone report and deliberately refers to current codes in the United Kingdom without repeating the details they contain. Designs may require consideration of specialist areas such as seismic design; where this is needed, the designer should take specialist advice and make appropriate provisions. The guidance seeks to suggest good practice and clarify interpretation of commonly used UK reference standards. It also illustrates areas of special concern in car park design where these differ significantly from the normal practice set out in building and construction codes. **The guidance principles are intended to be applicable worldwide.** It must be recognised that local, regional and national variations to design requirements exist and these should be confirmed in developing the design basis.

The report has sought to retain those parts of the previous guidance that were found to be of significant value and are still current, while updating other areas in the light of recent developments, design feedback and advice from operators. The suggestions and guidance contained in numerous good practice guides prepared by operators and recognised motoring organisations have also been considered to allow the report to reflect current and likely future expectations of facilities in public car parks. In particular, the facilities for security, payment and access control change rapidly with technological advances and will continue to develop. In such cases, the guidance is limited to discussion of generic types of systems in frequent use and the consideration of particular issues that need to be taken into account in developing an appropriate structural design and specification for a car park.

1.3 Status of the report

The Institution of Structural Engineers has produced this report as a guide and as such, it is only intended for use as a guide. It is not intended to provide the definitive approach in any situation, as in all circumstances the party best placed to decide on the appropriate course of action will be the engineer undertaking the particular project.

2.1 Introduction

2.1.1 Scope

This section is designed to assist in discussions with the client who wishes to commission a design for a car parking facility. Parking at grade, temporary demountable car parks and mechanically operated stacking devices are excluded from this document. It is advisable first to carry out a feasibility study before proceeding with a detailed design so that the viability of the project could be tested and all the key requirements established.

2.1.2 Design brief

The client and the design team should establish the design brief jointly. The purpose of the design brief is to establish the technical aspects and constraints affecting the design. It is not intended to define the commercial and contractual obligations within the design team. It is essential that the whole design team reviews the client's initial wish list. In this respect, it is important to carry out a feasibility study based on a number of sketch designs that satisfy, as closely as possible, the operational requirements of the client. It is only after such reviews that any benefits arising from variations to the original brief can be properly assessed (such as the position of entrances and exits or the maintenance strategy) to justify their reconsideration. The brief to, and responsibilities of, the individual members of the team at each stage of the design and development should be agreed with the client.

After the feasibility design, the whole brief should be reviewed again and any necessary changes agreed. However, since several alternative designs may have to be evaluated, it is important at the outset to agree with the client what criteria are to be adopted for the choice of the preferred solution. Clearly, this will often be on the basis of initial cost but should also consider such issues as whole life costs, building life, safety, security and charging strategy, together with further requirements of initiatives such as the Secure Car Park Scheme[2.1] administered by the British Parking Association. These issues having been taken into account, the client should formally sign off the accepted design brief before progressing to the detailed design stage.

2.1.3 The design team

The roles of the various members of the design team will depend on the client's expectations, the composition of the project team, and the procurement method adopted. A successful design will typically require input from the client's team, structural engineers, architects, landscape architects, planners, highway engineers, building services engineers, quantity surveyors, project managers and the contractor. Specialists such as fire engineers, acousticians and lighting experts may also be required.

However, there are other areas such as façade treatment, waterproofing, drainage, lighting and ventilation for which the design responsibility must be clearly established. The type of movement joints, membranes and drainage provision specified are critical to the durability of the structure. For this reason, the person taking responsibility for specifying such details must be aware of the design philosophy regarding durability and must fully appreciate the consequences of the chosen solutions for such details on the durability of the structure.

2.1.4 Limitations imposed by statutory requirements and public policy

Car-parking provision is constrained by the requirements that usually affect the design, construction and fit out of buildings but may also be affected by national and local policies aimed at traffic regulation. This may take the form of limited provision of parking spaces through application of the price-tariff mechanism or other devices. Many of these policies are being developed and are subject to change. It is therefore important that, before embarking on any project, the client confirms any requirements for accommodating future development trends, before entering into development of design options.

2.1.5 Mixed use structures

There are situations where a multi-storey car park has to be incorporated into a structure that will have other uses, such as car parking above or below a retail centre or offices. Ancillary services, in particular the sale of petrol, may also be envisaged.

When any fuel storage is proposed, zoning and special measures will be necessary, in which case specialist safety advice must be taken.

In such circumstances, it is essential to consider these matters in the design of the car park and its relationship to the design of the rest of the building. Where a future change of use or phased development is suggested, special details and arrangements may be required to provide durability, protection and flexibility for change. Leasing arrangements may also dictate aspects of an appropriate design solution. In structures integral to other developments, there may be whole-life benefits in separating car park elements vulnerable to chlorides from the main structural elements of the building above the car park.

2.2 Information to be considered for inclusion in the brief

2.2.1 Objective

The objectives of the client, particularly the purpose to which the car park building will be put and any requirement for future development, must be stated explicitly. A car park can be used for a number of separate purposes, or a combination of them, for example:

- a public car park operated as a public service for profit or through a subsidy
- a facility for a specific development where the pattern of use may be expected to remain reasonably constant throughout the day
- a facility for a given activity that will generate high peak demands at given times or lead to the assumption that there may otherwise be special design considerations. This could include provision for tidal flow.

The type and mix of vehicle for which the car park is required and whether there are likely to be any special requirements because of unusual vehicle dimensions should be stated.

2.2.2 The site

The brief should contain a full description of the site and its environs, with particular note of the adjacent highway network. The status of land at the time of writing the brief must be disclosed, particularly any restraints imposed by covenant or otherwise on building or access. The brief must clearly state the situation regarding statutory consents and with whom the client expects the responsibility for the progressing of these consents to lie.

Any specific requirements with respect to environmental and pollution policy should be clearly stated.

2.2.3 Site conditions

Data on site conditions should be determined and stated, particularly subsoil conditions including water table and drainage levels, as these are particularly important to the design of car parks. The arrangements for site clearance and collection of design data on ground conditions should be explained. Requirements for, and the value of, further investigations should be considered and agreed with the client.

2.2.4 Highway access

The purpose, layout, and present and future use of the adjacent highway network should be considered in the process of developing detailed entrance and exit arrangements and management policy. The impact of these issues can affect the viability of the project. Attention should be drawn to any known street improvements proposed, the possibility of their being required in consequence of the car park's construction, or any other matter that will affect the net site area available. The need to establish survey levels early on should be emphasised. The possibility that street lighting might be conveniently incorporated into the fascia of the structure where it abuts a public highway should be considered.

2.2.5 Statutory undertakers

Existing records of services within or adjoining the site and likely to be affected by the works should be identified and requirements for further investigations considered.

2.2.6 Building life

The life of a car park is conditional on the design specification and on the quality of construction and maintenance. The influence of these issues on the building life should be made clear to the client at the outset.

As a part of this process, it should be emphasised that research into car park performance has shown that if there is an absence of regular inspection and maintenance the rate of deterioration of certain elements can be rapid. To achieve the desired performance, an enhancement to the normal building specification will frequently be required.

2.2.7 Maintenance strategy

The client should agree the strategy to be adopted for the maintenance of the car park. This should include short-term maintenance such as sweeping, drain inspection and façade cleaning and also longer-term issues, such as periodic washing down of trafficked surfaces, painting, the policy for removing ice and snow, and the regular structural inspection of the car park. The last mentioned should include maintenance to ensure the integrity of waterproofing membranes, sealants and joints (see also Chapters 9 and 11).

2.2.8 Change of use

The client should indicate whether consideration is to be given at the design stage to a change of use of the whole or part of the car park at some time in the future. If this is to be considered, the client should agree full details of the changes to be considered. For example, the cost of including columns capable of supporting additional floors is nominal when compared to the cost and difficulty of finding a new site for the extension of a low-level car park.

2.2.9 Design and cost plan submission

The client should agree the manner and phases in which the completed scheme is to be submitted, together with a programme for the submissions. The method of procurement and associated programme implications should also be agreed.

It will be for the client to prescribe the manner in which the details of the cost plan are to be presented. The client should also include in the brief any cost information he has that is likely to affect the cost plan or economics.

2.3 Design considerations

2.3.1 Structural

The basic brief should:

- state any preferred structural materials or make it clear that the choice is left to the design team
- state the client's views on the use of specialist or bespoke materials (e.g. deck waterproofing, fire protection)
- specify required environmental and exposure conditions in relation to appropriate codes of practice or make clear that the choice will be left to the design team to eliminate any differences in interpretation. If an enhanced level of provision is required, reference documentation should be specified.
- state whether the structure is expected to be wholly above ground, wholly underground or a mixture of the two. The final recommendations may rest with the designer in the light of investigations undertaken, but any over-riding factors affecting the choice should be stated.
- state the basis on which the client will allow the design team to make decisions, without prior reference, and the frequency and mode of reporting required, including any particular hold points for approvals that will require a specific report or stage of completion.

2.3.2 Environmental

The client will need to clearly state how the finished building should look, drawing attention to any special circumstances that will affect the final choice. As a part of this process, the interrelationship between the vehicle containment system options and the appearance should be explained. The client's attention should be drawn to any requirement to protect adjacent buildings from noise, dirt or fumes – not only from vehicles but also from heating, ventilating plant, or cleaning equipment.

2.3.3 Appearance

The external appearance of a multi-storey car park is important (see Figs. 2.1, 2.2, 2.3 and 2.4). The normal principles of architectural design apply. It is worth noting that, as car parks seldom have fully clad elevations, the structural form can have a dominant influence (see Fig 2.5).

It is unfortunate that the finish and detailing of any building are often the first elements to suffer when costs

Fig. 2.1 External façade of Hines Meadow car park, Maidenhead

Fig. 2.2 An example of a façade with strong vertical features

Fig. 2.3 An example of a façade with strong horizontal features

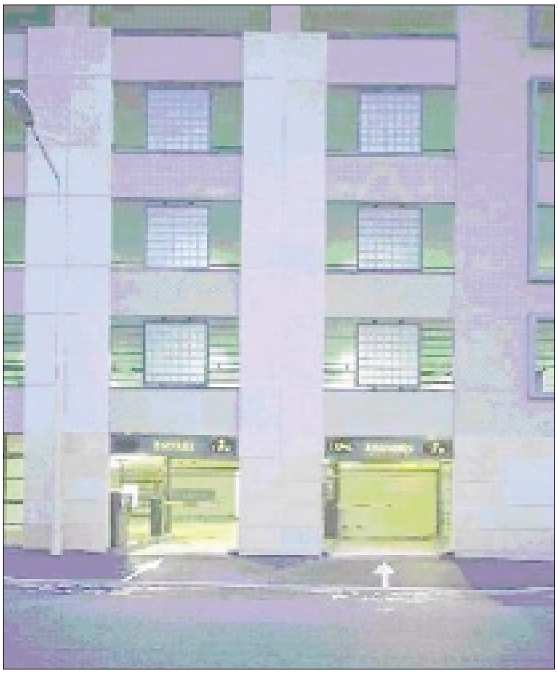

Fig. 2.4 Façade of Berthelot car park, Lyons

have to be reduced. As there is generally so little margin available in multi-storey car parks, this short-term view has in the past had a disastrous effect on the quality of the appearance and long-term performance. The great difference in quality between the best and the worst designs suggests that cost alone is not always the most important factor in ensuring a satisfactory quality of appearance. For good architecture and engineering, there are no substitutes for skill, experience and sympathetic handling at the design stage.

The treatment of the site surrounding a multi-storey car park can have a considerable impact on the building itself: even in urban situations there is opportunity for hard landscaping and planting (see Figs. 2.6 and 2.7). Intelligent choice of both hard landscaping and planting can be an important way of relating and connecting the car park with other buildings, and is also of great value in softening the visual impact of the car park. Vehicle and pedestrian access points provide an opportunity for treatment to avoid monotony. Shrubs, trees and flowers can help, particularly at these points, and will be much appreciated by users. In designs for urban areas, buildings are not necessarily marshalled in terraces and parades. This feature of urban planning gives scope to set back structures from the highway and facilitates the use of external ramp systems and the siting of entrance and exit controls outside structures.

External ramps may go against many of these positive siting issues and can sterilise large areas of the site. The sides of the ramps offer obvious opportunities for careful thought and interesting treatment. Straight ramps are usually more difficult to treat than curved. However well ramps are dealt with, they are seldom considered things of beauty and often need to be hidden.

Although the scope for internal decoration of multi-storey and underground car parks is limited, to gain full public acceptance, people must be attracted to them. A light, airy and welcoming interior appearance helps. Carefully designed lighting and well-chosen colour schemes can do much to improve the internal environment (see Fig. 2.8(a) & (b)). These should not be applied all over but are particularly valuable to denote access routes and key positions for drivers and their passengers when they become pedestrians. Vandalism is a perpetual hazard but the cost of vandal-resistant surfaces for large areas of the interior can be prohibitive. Again, key danger areas should receive special attention.

Full consideration of services required in the car park must be taken at the design and planning stage to permit full integration. This will usually include signs and signposting methods, as well as power, lighting, security and fire control systems.

2.3.4 Town planning

Consideration should be given to the requirements of the local planning authority, and any documents already in the client's possession should be supplied with the brief. Special planning requirements, particularly in respect of preservation, conservation and redevelopment, should be taken into account.

The provision of parking is a significant element of transport policy since its presence or absence has a major influence on the choice of transport mode. It can be argued that *all* parking is related to development; indeed, local authorities use parking policy to influence the demand for travel by private car within their areas. Such policies cover both parking provided by local government or the private sector and parking provided specifically in association with new development or redevelopment proposals.

Development projects vary considerably in scale, content and location. Mixed land uses are increasingly being provided on the same sites or nearby. Operational economies of scale lead to larger developments. The resulting demands for parking can lead to parking provision that can be complex and environmentally intrusive. Addressing the balance between operational requirements and environmental impact presents a challenge for designers.

Planning policy guidance relating to development is regularly issued. For example, the UK Government has for many years issued Planning Policy Guidance notes (PPGs) covering a wide range of land uses and designed to provide a consistency of approach across different regions of the country.

A planning authority will consider a planning application within the context of its approved development plan. That plan itself has to be consistent with the hierarchy of adopted policies and plans. These are typically:

- Planning Policy Guidance
- Regional Planning Guidance
- Structure Plans
- Local Plans, and
- Spatial Development Strategy.

For metropolitan and unitary authorities in the UK, a single Unitary Development Plan (UDP) may replace the Structure and Local Plans.

These policy documents significantly affect both the location and the nature of new developments, typically including parking guidelines that should apply. Many local authorities publish parking guidance, applying various requirements according to the location of the site and its proximity to public transport. These local guidelines, which translate national policy into local

Fig. 2.5 Stockley Park car park, Heathrow. The structural form dominates the appearance of the car park

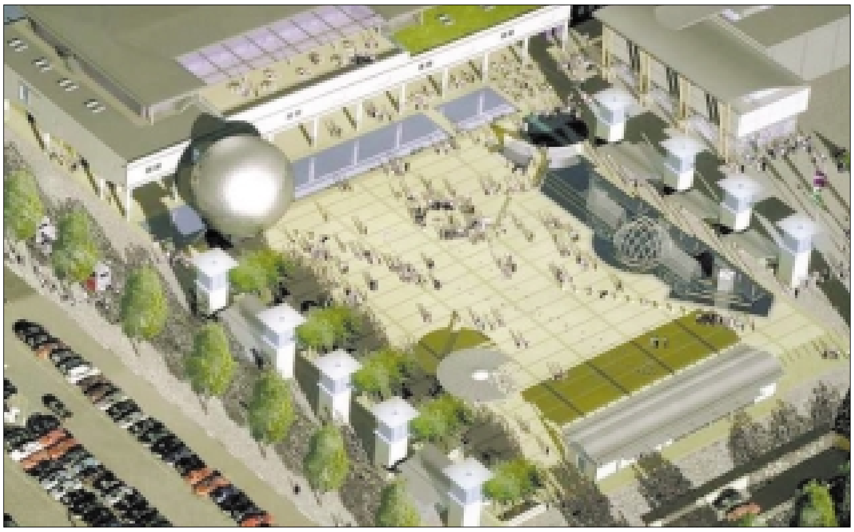

Fig. 2.6 New World Square underground car park, Cannons Marsh, Bristol showing effective use of landscaping

Fig. 2.7 Example of urban planning showing effective use of landscaping and siting

Fig. 2.8 Example of decoration showing good use of quality finishes, lighting and security measures

(a) before refurbishment (top left)

(b) after refurbishment (top right)

situations, must always be considered when designing a new development.

Where Regional Planning Guidance (RPG) is issued – for example by the UK Government – it is normally formulated in the light of advice from local authorities addressing strategic issues such as the provision of housing, employment and transport.

Structure Plans, such as those prepared by County Councils, and Unitary Development Plans are normally compatible with RPG to provide strategic planning guidance over a wide area. Local Plans, such as those developed by District Councils, cover a smaller area and normally conform to the Structure Plan. Local plans typically provide the detailed planning framework and constraints applicable to specific sites. The combination of all of these plans and policies provides the framework within which decisions are made about new development proposals. Planning-led systems of development control are frequently used. For example, since 1991 in the UK, planning decisions must be in accordance with development plans unless material considerations indicate otherwise. Similar arrangements exist in Northern Ireland.

Development proposals themselves are typically dealt with through applications to the Local Planning authority for consent. This can either be a consent in principle, with reserved matters to be determined later (outline application), or a consent in detail, which will define the exact scale and nature of the development, including parking provision and means of access.

In preparing a planning application, the developer and design team need to consider all guidance and policies that may affect a scheme and specifically transport issues. Documents supporting such an application should deal explicitly with these issues.

Transport implications will significantly influence decisions on identifying development sites for different purposes, and supporting documents should seek to quantify the impact of the proposal. 'Before and after' scenarios may have to be considered or comparison made with alternative proposals.

Although forecasts will continue to depend heavily on predictions of growth and use of private cars, new developments are increasingly required to consider, and often encourage, other modes of transport and to provide for them within the planning of infrastructure. It is therefore essential that, in designing car park facilities, proper consideration be given to providing facilities that can safely be used by mobility-restricted users, pedestrians, cyclists and public transport users as well as by private cars and service vehicles.

2.3.5 Building regulations and other legislation

The brief should include any exchange of correspondence with the local authority concerning application of relevant regulations and legislation, which may have implications for the final design. The brief should either list the relevant local regulations and legislation or cite an alternative regulatory regime agreed with the client.

The client has responsibilities to comply with national and local Health and Safety legislation. For example, in Europe this will include Health and Safety Directives, and specifically in the UK, the *CDM Regulations*[2.2, 2.3]. Any local variations in regulations must be considered and accommodated. For example, in Northern Ireland, *The Building Regulations (Northern Ireland)*[2.4] apply and are supported by technical booklets. In addition, separate *Construction Design and Management Regulations (NI) 1995*[2.5] apply.

In assessing risk, designers should consider the dangers that can occur in multi-storey car parks from failure of barrier connections, poor maintenance regimes and deterioration of key structural elements leading to failure by corrosion of connections. To mitigate the consequences and reduce the probability of recurrence, potential weaknesses that have been identified and means of safe access for maintenance should be considered.

In completing the structural design, the designer should consider the construction sequence, stability and access requirements needed to complete the construction process and in-service maintenance safely. Design choices must be made in the light of the CDM regulations, which require designers to eliminate or reduce risk during both construction and maintenance.

2.4 Operational criteria

2.4.1 General

It is recommended that a schedule of operational criteria should be prepared after feasibility studies of:

- traffic requirements
- site requirements
- accommodation and operational requirements.

For smaller car parks (i.e. with fewer than 200 spaces), a common study may serve these three requirements. Larger parking developments may generate high traffic flows, and the need to analyse traffic and site requirements is of primary importance. In such cases, it is recommended that both traffic and site feasibility studies be carried out. In every case, adjacent concurrent or proposed developments should also be taken into account in the studies.

Unless the studies require any special dimensions to suit operational criteria, it is recommended that car parks use the dimensions in Chapter 4.

2.4.2 Traffic feasibility and impact

If a separate traffic feasibility study is required, it should include the external road system. The traffic study provides the flows required for the site study and identifies key requirements. For example, in urban areas with high car-park flows, the siting and design of entrances and exits may be critical. The traffic feasibility study also establishes the capacity (see Section 2.4.5 (a)).

Many new developments are of a size or type that generate additional journeys on the adjoining transport infrastructure. This additional demand may necessitate changes to the highway layout or to public transport services. Wherever possible, opportunities should be taken to provide direct access to public transport and to pedestrian/cycle infrastructure, thus helping to modify the total transport impact.

The developer or promoter will normally be required to provide a full and detailed assessment of how trips to and from the development might affect the highway network and/or pubic transport facilities. The transport impact assessment should be an impartial description of impacts and should include both positive and negative aspects of the proposed development.

Transport impact assessment addresses two related issues:

- the effects of additional traffic on the safety and efficiency of the existing network (volume/capacity);
- the effects of additional traffic in terms of noise, pollution and visual intrusion (environment).

Traffic impact assessments are now usually required from developers in support of a planning application, the primary responsibility resting with the developer, not the Local Authority. Standard formats for assessment are available and may be required. For example, The Institution of Highways and Transportation, with the endorsement of the Department of Transport, has published *Guidelines on Traffic Impact Assessment*[2.6].

Before undertaking a full Traffic Impact Assessment (TIA), a scope analysis should be carried out by the developer, in conjunction with the Planning and Highway Authority, to agree the key aspects to be addressed by the TIA. This analysis study should set out details of data to be collected, the area of analysis, key junctions to be considered, the methodology to be adopted and the years for assessment. Such a study will provide a basis for assessing the level of resources that will be required to undertake the TIA. It will also be invaluable to all involved and should ensure that work is not undertaken unnecessarily and that resources are directed to those aspects requiring most attention.

Before further time and resources are devoted to an application for detailed consent, approval in principle for a particular type of development is often sought by way of outline planning consent. The access arrangements for a site is one area of technical analysis where outline conceptual designs may not be sufficient to determine the practicality or safety of a scheme. An outline design often contains insufficient information to enable a highway authority to enter into an agreement with a developer, relating to the costs and layout of the access, and therefore needs to be treated with caution. If appropriate agreements are not determined at the outline stage, it may not be possible to reach a satisfactory outcome at the detailed application stage. Consequently, even with an outline application, access details may need to be provided.

The hierarchy of decision-making and responsibility for obtaining consents and planning permissions must be agreed within the project team and the client. It should be noted that planning decisions might not be determined solely by the local planning authority. For example, the Secretary of State, as The Highway Authority for trunk roads and motorways in the UK, has powers to direct the local planning authority to refuse an application on highway grounds, whereas the Local Highway authority can only advise the local planning authority.

2.4.3 Site feasibility requirements

At this stage, the functional design appropriate to the site and parking requirements is prepared. This process may involve preparing trial designs in accordance with the client's brief and traffic requirements. The performance requirements determined at this stage are given in Sections 2.4.5 (b) and (c).

Proposals for new developments will include layouts of access roads and car parking. Pedestrian access, facilities for cyclists and the design of public transport infrastructure, such as bus stops and shelters, should also be considered in detail.

Where highway authorities require independent safety audits in support of proposals for new highway works associated with development proposals, they should be undertaken in accordance with relevant guidelines (e.g. IHT Guidelines[2.7]).

Where parking space is to be provided, the following points should be considered when preparing a development plan.

Accessibility and convenience

The location of parking and loading areas should be close enough to the building or land they serve to reduce the likelihood of drivers parking indiscriminately to avoid walking. Acceptable proximity may be affected by the nature of the walk involved. A longer walk may be acceptable in a safe and pleasant environment with easy gradients and good lighting. As a guide, 400m is a generally accepted maximum walking distance.

Disabled persons

Location is particularly important for disabled persons and any allocated spaces should be as close as possible to the destination, wide enough for wheelchair access and connected to the destination without steps. Ramps or lifts may be necessary.

Vehicle access and safety

Geometric standards that allow reasonably comfortable clearance for the types of vehicles for which the spaces are provided should be applied. Special attention will be necessary at turning points and to give adequate headroom and ground clearance on ramps. Good standards of visibility must be maintained at all times, particularly when car park access joins a main road. It is generally necessary to ensure that queues of vehicles waiting for access do not extend back to the main road.

Operation and maintenance

Some form of access control is generally needed so that parking spaces are used in the way that is planned. Sometimes, this might extend to fully automatic doors, grills or even cages for individual vehicles to prevent vandalism. The running surface should be free-draining and resistant to attack by oil or petrol. It may also be necessary to employ attendants to ensure that operational and visitors' spaces are used correctly. Good design can minimise the need for supervision and maintenance. Robust and vandal-proof light fittings and safety barriers may have to be provided.

Impact on surrounding road network

The number of spaces provided should relate to the capacity and functions of the surrounding road network and the characteristics of the use of the particular development.

2.4.4 Accommodation and operational requirements

To complete the schedule of operational criteria, accommodation and operational requirements should be listed and agreed with the client early in the development of the project concept (see Sections 2.4.5 (d) to (h)).

2.4.5 Schedule/checklist of operational criteria

The following schedule is not exhaustive and only indicates the principal points that may need to be considered.

Points to be considered, discussed and agreed with the client, before starting each of the agreed design stages are:

(a) Capacity

- The number of car spaces required (including those reserved for special needs), usually stated as a minimum capacity
- If part of the car park is to be used for a special category of user, or vehicle, or part of it is to be partitioned as individual lock-ups, a breakdown into types of accommodation is required
- The capacity is usually derived from the results of a parking study for the development that the car park serves; alternatively, the requirement may be to make appropriate use of a particular site
- Phasing to suit demand and the use of temporary structures for event parking.

(b) Layout

- Floor and ramp arrangement
- Arrangements of entrance/exit lanes and provision of reversible or tidal access lanes
- Arrangement of control gates, including the preferred method of checking entry and exit
- Reservoir space at entry
- Reservoir space at exit
- The arrangements required for normal and emergency pedestrian entrance, egress and circulation
- Provision for the disabled
- Escalators and lifts. Requirements should be specified; any special requirement, e.g. provision for shopping trolleys, should be stated
- Required vehicular and pedestrian access and exit points, usually minimised, including those to be kept under CCTV surveillance
- Areas where fuel storage is to be allowed
- Areas where car washing is to be allowed.

(c) Dimensions and headroom

- Stall size (width and length). Where there are special requirements, the appropriate stall sizes should be stated for each requirement
- Aisle width
- Clearway widths
- Helical ramps: layout and minimum outer kerb radius
- Required headroom
- In mixed-use buildings, the headroom required for floors not used wholly for parking.

(d) Internal accommodation requirements

- Cash-kiosk requirements, including fittings
- Managers' office floor area and fittings
- Staff-room floor area and fittings
- Staff toilet provisions
- Toilet accommodation required for car-park users, including provisions for the disabled
- Electricity substation requirements
- Storage accommodation
- Management control room to be provided.

(e) Mechanical and electrical equipment

- Requirements for ramp heating
- Requirements for plug-in battery charging or engine-heating systems
- Entrance and exit control and payment systems together with audit requirements and flexibility required for replacement/refurbishment
- Vehicle movement detection, counting systems and monitoring requirements
- Performance requirements and capacities for lifts
- Expected rate of air change and maximum permissible carbon monoxide content at any point in the building
- Whether forced or natural ventilation is to be used
- Temperature range to be maintained in the building, in particular the necessity for heating staircases
- The general arrangements expected with regard to sprinklers, fire points, cut-off doors and alarm systems
- Requirements for access to emergency vehicles; see Section 5.1.7
- Means of protection from mechanical damage and interference by unauthorised persons
- The standard of lighting expected and the method of control required
- Surveillance and security arrangements affecting the geometry of the structure
- Requirements for provision of CCTV, to cover all areas inside and out
- Secure access provisions, e.g. swipe card and automated facilities to prevent unauthorised access
- Requirements for provision of car wash facilities.

(f) Finishes, road markings and signs

- Preference for finishes or facing materials, including the use of walls for advertising
- Restrictions on floor finishes, e.g. areas required to

facilitate use of shopping trolleys, and any compatibility requirements when using membrane waterproofing systems

- Illuminated direction signs and floor markings to facilitate circulation may be required, together with reference markers to enable users easily to retrieve their vehicles
- Requirements for external signing should be stated.

(g) Operational and maintenance considerations

- Preferred method of providing drainage to the parking areas and ramps, e.g. pumped or gravity systems
- Data relating to the local drainage infrastructure
- Method of operation and control of pumps
- Levels of standby power required for ventilation, lighting and pumping equipment
- Maintenance and services requirements
- Requirements for bird roosting control, e.g. netting
- Frequency of major maintenance
- Level of standby and automatic monitoring systems
- Means of access required for replacing fittings and cleaning
- For basement car parks, the acceptance criteria and required environment must be discussed and agreed with the client.

(h) Barriers

- Requirements for protection barriers for vehicles and pedestrians. The efficient design of the vehicle restraint system is essential as the cost of barriers represents a significant proportion of the cost of the structural frame
- Preferences for forms of barriers and the level of maintenance.

(i) Liaison and reporting

- The arrangements to be made to keep the client informed of project developments
- Confirmation of key decision points and levels of authority to implement changes
- Confirmation of programme milestones and dates when specific approvals and reporting are envisaged.

2.4.6 Cost benefits

The whole-life cost benefits of various solutions should be discussed with the client at this initial stage. In addition to the usual cost-benefit analysis that should be carried out for the various structural options in terms of spans, materials, user benefits, etc., an analysis of the various recommendations contained in this document concerning durability will require client decisions about the life of the structure, the maintenance regime and their effect on costs. A more costly robust initial solution is likely to have a longer-term benefit in terms of maintenance and life-cycle costs.

It is important to involve the client in this process and to agree with them the strategy for determining the most suitable solution.

2.4.7 Choice of solution

Finally, it is essential to remember that any given problem or set of criteria often has more than one satisfactory answer. It is clearly important that reasonable solutions be considered, and so the client's brief should not be unnecessarily restrictive but should be broadly based to give the designers the opportunity to exercise their skill, experience and judgment in formulating proposals for the most effective and economic parking facilities.

References

2.1 Association of Chief Police Officers in England and Wales, British Parking Association, Automobile Association and Home Office: *The Secured Car Park Award Scheme – Guidelines For Self Assessment,* (available from British Parking Association). London: ACPO, 1995

2.2 *Construction (Design and Management) Regulations 1994.* London: TSO, 1994

2.3 Health and Safety Executive: *Managing health and safety in construction.* HSG 224. HSE, 2002

2.4 *The Building Regulations (Northern Ireland) 2000.* London: TSO, 2000

2.5 *Construction Design and Management Regulations (Northern Ireland) 1995.* London: TSO, 1995

2.6 Institution of Highways and Transportation: *Guidelines on traffic impact assessment.* London: The Institution, 1994

2.7 Institution of Highways and Transportation: *Guidelines for the safety audit of highways.* London: The Institution, 1996

Fig 3.1 Q-Park Museumplein, Amsterdam – thoughtful design to create a safe and secure environment

Fig 3.2 New World Square car park, Cannons Marsh, Bristol, showing effective methods of illuminating the interior

Fig 3.3 Example of an illuminated interior

3.1 Operational design requirements

3.1.1 Introduction

The design, capacity and operation of a multi-storey car park will be determined by such factors as:

- amount of land available
- number of spaces required, bearing in mind the need to justify the capital costs in terms of the expected net revenues
- impact on the external road network of the traffic generated by the car park.

Short-stay, usually higher-priced, parking in the more central locations will have a greater turnover for a given level of occupancy and will therefore attract more traffic throughout the day. Long-stay parking – especially when directly associated with a large office or factory building – will produce high traffic flows only in the morning and evening peak periods.

Car parks must be carefully managed if they are to provide a high standard of service. Long-term maintenance plans, covering the fabric of the building, running surfaces and equipment, must be drawn up so that appropriate budgetary provision can be made. Day-to-day attention to cleaning, removal of graffiti, repair of defective lights, signs, lifts and ticket machines is essential. Staff training is also important to ensure service levels are maintained.

The Association of Chief Police Officers in England and Wales, in partnership with the British Parking Association, the Automobile Association, and the Home Office, have prepared The Secured Car Park Award Scheme[3.1]. This is an initiative to encourage those responsible for car parks to improve security as a means of reducing criminal activity, the fear of crime and the perception of crime in all car parks and vehicle-retention areas. The appearance can significantly affect the perceived security, which can be improved by careful use and specification of:

- lighting levels
- appropriate column sizes, e.g. avoiding large columns
- painted internal surfaces
- additional floor finishes
- sight lines.

The objective of the scheme is to certify car parks that have introduced effective measures to create a safe and secure environment (see Fig. 3.1). Many of the targets can be achieved by thoughtful design and apply to car parks in any location.

It is important that surveillance, either by human presence or by CCTV, covers all areas of the site. The layout should seek to minimise or avoid out-of-sight areas or obstructions that provide hiding places. Landscaping and boundary features should not obstruct surveillance or provide opportunities for concealment. High levels of illumination are required throughout (see Figs. 3.2, 3.3 and 3.4) and light fixtures and fittings should incorporate vandal-resistant features, with cables and wiring securely enclosed. Parking areas should avoid blind spots and vehicle and pedestrian access routes should be monitored with an effective CCTV system. Payment meters should be positioned in busy areas that are well overlooked. Adequate sight lines should be provided to enhance safety at points where traffic movements

Fig 3.4 Champs Elysées Pierre Charron underground car park, Paris, showing effective methods of illuminating the interior

and flows conflict such as at the exit points from ramps between floors. Similarly, good visibility is vital where pedestrian access routes need to cross principal circulatory traffic routes.

Where statutory requirements allow, lifts should open directly onto car park levels or onto wide, well-illuminated and unobstructed landing areas. Vandal-resistant buttons and panels are suggested along with vision panels in lift doors. Stairways should be wide, preferably with open balustrades to allow good visibility (see Fig. 3.5). All access and exit points should be fitted with gates or grilles.

To manage the car park, there is usually a control room or, with large car parks, a control suite. There can be benefits in discussing security arrangements with the client and the police crime-prevention officer. As well as normal security measures and CCTV systems, there may be requirements for external telephone lines, personal attack alarms, operation of barriers from a kiosk, door locks to relevant standards, and

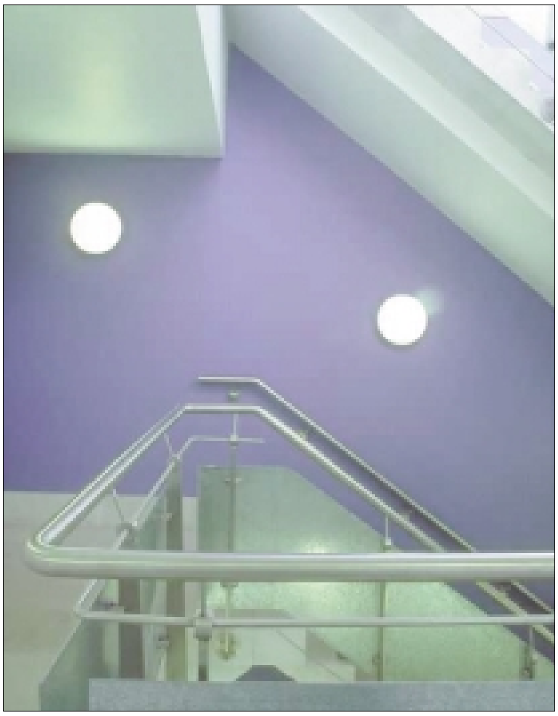

Fig 3.5 New World Square car park, Cannons Marsh, Bristol, showing details of landings and stairways

protective screening or cash-handling facilities. The level of security and principles for the provisions required should be discussed and agreed at an early stage of the concept development.

3.1.2 Capacity

The number of spaces available in a car park is termed its storage, or static capacity, as distinct from the dynamic capacity, which is the maximum in-flow or out-flow of vehicles. The largest single determining influence on dynamic capacity is usually the type of control employed at entry and exit, including the way any charges are collected. With minimal formalities on entry or exit, the dynamic capacity is determined by the capacity of the circulatory aisles. As a general rule, the dynamic capacity should be sufficient to permit up to 25% of the static capacity to enter or leave the car park within 15 minutes (i.e. up to 100% turnover in an hour).

The maximum practical occupancy is likely to be lower than the theoretical static capacity, particularly where there are no marked bays or car park staff to ensure disciplined parking. In addition, since cars are arriving and departing simultaneously, those already in the car park searching for a space may miss newly vacated spaces. Where entry is controlled, deliberate margins of about 5%, depending on size and turnover, are sometimes introduced to overcome this problem. Where parking discipline is particularly poor and spaces between columns are badly designed, actual occupancy can be as much as 50% below the theoretical capacity.

3.2 Dynamic capacity requirements

In regard to design geometry, the aisle capacities, turnover, ramp capacities and vehicle reservoirs are considered critical to the dynamic operation of the car park.

3.2.1 Aisle capacities

The dynamic capacity of an aisle is based upon its width, bay dimensions, proportion of cars reversing into bays, and lighting levels. RRL Report LR221[3.2] examines simple bays/aisle systems and identifies ways of calculating the inflow and outflow capacities for tidal flow.

TRRL Report 1126[3.3] gives the turnover capacity, which is more appropriate to short-stay car parks. However, as the inflow and outflow capacities apply to long-stay car parks or periods of peak entry and peak exit, caution has to be applied for short-stay facilities. Retail centres can experience constant arrivals and departures, which effectively reduce aisle capacities. To overcome this and to increase car-park efficiency, the introduction of clearway ramps can be considered to bypass parking aisles. Typical aisle capacities for given design bay dimensions are shown in Table 3.1.

Table 3.1: Calculated capacities for 6m aisles with 90^{o} parking

Bay	Width (m)	Length (m)	Aisle capacity (cars/hour)		
			Inflow	Outflow	Turnover
Long-stay	2.3	4.75	865	740	400
Standard	2.4	4.75	905	765	415
Short-stay	2.5	4.80	955	790	435

These dynamic capacities should be compared with the expected inflows and outflows for the car park to determine circulation and ramp-location details. Usually, traffic flow demands are considered as dependent on the trip purpose: where this data is not available, common practice is to assume a demand equal to one-quarter of the car park static capacity arriving or departing over 15 minutes. This simple method enables design concepts to be developed before detailed assessments, normally undertaken by a highway engineer.

3.2.2 Vehicle speeds

Free-flowing conditions are essential to the economic fulfilment of dynamic capacity and can override the benefits gained from increasing vehicle speed. Operators generally display speed limits within car parks to minimise risks and improve pedestrian safety. A limit of 8km/h (5mph) is typical, although design criteria for the geometry and barriers are normally based on 16km/h (10mph) (see Section 3.3.5).

3.2.3 Ramp capacity

The average capacity of straight up-and-down ramps is about 1,850 cars per hour. Reference 3.2 gives a method of calculating capacity of bends on accessways and ramps. When applied to the advised circular ramp radii of 7.5m, 9.0m and 12.0m measured to the outer kerb with lane widths of 3.65m, operational capacities are respectively 1200, 1460, and 1700 cars per hour. Narrow ramps with poor visibility can significantly reduce the flow capacity as drivers exercise greater caution for safety.

3.2.4 Vehicle reservoir at entrance, and entrance layout

The short-period arrival rate of cars may exceed the entrance barrier capacity (and/or the dynamic capacity of other parts of a car park). To prevent a queue extending on to a public road, a vehicle reservoir should be provided.

Where drivers may have to wait to enter a car park because it is full, the layout of the entrance reservoir should preferably allow them to return to the street or road without entering.

3.2.5 Vehicle reservoir at exit

If an exit barrier is to operate at its design capacity, drivers must be able to pull away as soon as the barrier opens. If cars have to wait to enter the road, a queue may form and obstruct the barrier to an extent that unacceptably reduces capacity. In these circumstances, a vehicle reservoir will be required between the exit barrier or barriers and the road.

The calculation of storage area should be undertaken using junction-analysis software, such as the UK Transport Research Laboratory programs, which calculate the vehicle queues for various traffic-flow conditions and type of junction.

3.2.6 Bay turnover

Turnover, or the number of times a bay is used during the day, is a measure of the car-park use. It is calculated by dividing the number of cars entering the car park during the day by the number of bays in the car park. For instance, a car park used solely by drivers parking all day while at work would have a turnover of 1 if fully occupied and below 1 if not. Turnovers vary significantly and typical bay turnovers in excess of five cars per day have been reported for short-stay multi-storey car parks.

A high turnover is associated with short stays and considerable internal movement. Attention is drawn to the recommended bay width of 2.50m for short-stay parking as opposed to 2.3m for long-stay. The additional width facilitates loading/unloading and helps drivers manoeuvring in and out of bays. In addition, for a high-turnover car park, short multiple-search paths are desirable. These should be laid out systematically to help drivers searching for a vacancy, while minimising the number of vehicles circulating (see Section 4.4.7). It is suggested that the split-level layout is unlikely to prove satisfactory for a high turnover owing to the complicated search paths associated with certain bays. For a high turnover, the flat-deck layout is likely to be better, with clear-span construction to give drivers good visibility and to help them manoeuvre in and out of bays. Clearway ramps both up and down may be required. Directional and informational signing for drivers and pedestrians is also required.

3.2.7 Design variations

Car-park design must consider the customer carefully and provide a system that is simple and safe. It must also be compatible with the locality and follow the guidelines established by the Local Planning Authority in terms of appearance and scale. These principles of use and planning tend to control the size of the car park, circulation facilities, and geometric design requirements.

The design details presented provide general guidance only and local variations will occur. It is also acknowledged that, although primarily for UK application, the design parameters are functions of European car design and driver behaviour, and thus can be applied to car parks throughout Europe. Where the approach is used outside the UK for concept development, local building regulations will have to be examined along with insurance requirements.

3.3 Traffic management

3.3.1 Introduction

For the full dynamic capacity of a car park to be attained, traffic must flow smoothly into, out of and within the building, enabling drivers to enter, park and later locate their car and leave as easily and quickly as possible.

To prevent queuing at the entrance and any associated impact on the external road system, entry capacity should be equal to, or greater than, the maximum expected arrival rate. An access road should provide a queuing reservoir for those times when the entry to the car park is operating at or near its dynamic capacity. It should be designed to assist transition from the higher speed travel on the external road network to walking speed within the parking area. Access roads should be used exclusively for entry into the car park so that traffic on the adjacent roads is not unnecessarily delayed.

The rate of outflow at the exit from the car park should not exceed the reserve capacity of the road onto which it discharges and priority must be retained on the external road system, so that any queuing takes place within the car park.

Wider bays permit easier and quicker manoeuvring into and out of bays, do not impair aisle capacity and make getting into and out of vehicles more convenient. Any columns between bays should be positioned so as not to obstruct the opening of car doors. The additional width for disabled parkers may be shared between two adjacent bays.

Smooth and rapid traffic flow can be achieved only by careful design of the car park and by intelligent selection of the parking-control system. It is apparent that the layout, location and function of each car park will influence the selection of the parking-control system to be adopted.

Traffic control is enforced in car parks at various stages:

- at entry
- within the car park
- in the collection of parking fees
- at the exit.

3.3.2 Entry and exit controls

The type of any control[3.4, 3.5] to be used on entry and/or exit is most important and usually determines, or will be determined by, the way charges are collected. In general, entry to a car park should not be permitted unless an appropriate space is available. Entry may be controlled by a lifting-arm (see Fig. 3.6) or a rising-step barrier (see Fig. 3.7). Exits may be controlled in a similar way or by using collapsible plates, hinged on their leading edge, to ensure that vehicles can only pass over them in one direction. If parking is free, or if payment is made on entry or using a pay-and-display system, exits need not be controlled.

Entry control
Whenever entry has to be controlled, either for charging purposes or to prevent congestion, the choice has to be made between lifting-arm and rising-step barriers. Traffic signals, CAR PARK FULL signs, ticket-issuing machines and SEASON TICKET ACCEPTABLE machines may accompany these. Where provision for motorcycles is required, special entry and exit facilities are recommended.

Lifting-arm barriers
Lifting-arm barriers (see Fig. 3.6) are generally preferred since they are easily visible to the motorist and straightforward in operation. While the mechanism is robust, the arms are easily damaged and may require frequent maintenance and repair through accidental damage or vandalism. Incorporating shear bolts or breakable plates to prevent damage to the mechanism simplifies repair. Where barriers have to be sited where headroom is restricted, articulated arms may be needed. Some barrier and vehicle detection systems can be inconsistent when required to detect motorcycles. Accordingly, great care is required when selecting barriers for use in car parks accessible to motorcycles. A separate control lane for the sole use of motorcycles is generally preferable.

Rising-step barriers
Rising-step barriers (see Fig. 3.7) consist of a steel plate that can be mechanically raised from its 'down' position level with the roadway to its 'up' position in which it protrudes above the road surface to form a barrier to traffic. Such barriers, which are more expensive than lifting arms, have been found to be more vandal-resistant and to provide a more positive vehicle barrier. Cases have been reported of vehicles being damaged either by barrier malfunction or because they were not immediately visible to motorists. It is recommended that they should always be accompanied by a traffic signal that shows red until the barrier is fully lowered, thus avoiding possible damage by equipment malfunction or driver error.

Because of their greater vandal resistance, rising-step barriers have been used with some success for controlling unattended car parks, often in conjunction with collapsible traffic plates at the exit.

3.3.3 Capacity of entry lanes

The vehicle capacity of entrance lanes will depend on how fees are collected. The maximum capacities (in general terms) quoted by manufacturers for each system are shown in Table 3.2.

In designing car-park entry lanes, it is important to recognise that maximum efficiency will be achieved when motorists can drive into the car park in a straight line and that capacity will be reduced if bends are introduced or there are poor sight lines. When tickets have to be obtained ahead of the barrier arm, it is particularly important to ensure that drivers can remove tickets from the issuing machine with ease while seated in their cars (see also Section 3.4.8). For countries such as the UK that drive on the left, this can be particularly difficult to arrange with a left-hand bend

Fig 3.6 Lifting arm entry barrier

Fig 3.7 Rising step entry barrier

Table 3.2 Maximum capacities for entry lanes

Fee collection system	Capacity of a single lane (cars/hour)	
	Lifting-arm barrier	Rising-step barrier
no ticket issue	550	500
automatic ticket issue	450 (Note 1)	450 (Note 1)

Note 1: Experience suggests that these maximum capacities may need to be reduced by 20% to allow for local conditions.

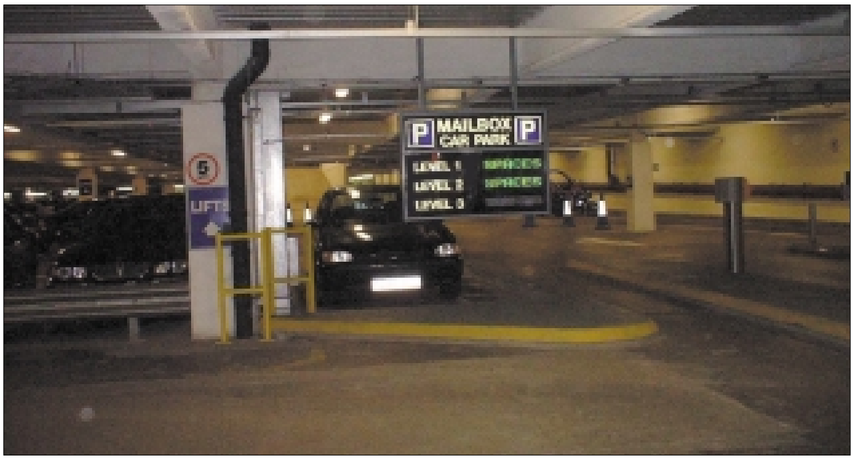

Fig 3.8 Illuminated variable message sign

Fig 3.9 Guidance sign showing available occupancy of car parks

Fig 3.10 Guidance sign showing available occupancy of car park

immediately before the entrance.

Where access is by way of a ramp, the entry control should never be located on the ramp and, wherever possible, controls should be sited to avoid queuing on the ramp itself.

3.3.4 Control within the car park

Once motorists have passed through the entrance control, their aim will be to find a convenient vacant bay as quickly as possible. To ensure convenient and efficient operation, a clear system of signs and floor markings is essential. With car parks housing up to 400 to 500 cars, only the main routes need be signed, drivers being left to locate vacant bays. However, in larger car parks, this approach is too haphazard and usually results in delay and inefficiency. It is therefore usual to divide large car parks into units of 100 to 300 bays and to guide incoming cars to units with vacant bays. This guidance can be achieved by means of electronic detectors that activate vehicle counters that constantly monitor occupancy. These counters automatically switch internally illuminated signs (see Fig. 3.8) to guide incoming motorists to units with vacant bays. While it is unusual to install such a guidance system in car parks of 500 bays or fewer, there may be circumstances where it will be helpful to motorists to do so.

While electronic control systems are often necessary in large car parks, for car parks under 500 bays they should be avoided whenever possible by design. This can be achieved by providing a logical search path that the incoming motorist will follow through the car park and which will enable them to find a parking space with ease. It is recognised that there will be instances where, in order to take advantage of small or awkward shaped sites, it will be necessary to construct car parks that rely entirely for their successful operation on electronic control equipment, and this may be justifiable in congested city sites. However, as has been noted above, a straightforward and smooth-flowing design is preferred.

3.3.5 Speed control

Because car parks are a mixed environment of pedestrians and vehicles, a speed limit of 8km/h (5mph) is recommended, a limit generally recognised as minimising the risk of serious injury to pedestrians. Nevertheless, the geometry and vehicle restraint barriers are normally designed for 16km/h (10mph).

The common forms of vehicle speed control are 'sleeping policemen' (road humps) or road-narrowing using post and barriers. It is important to note that 'sleeping policemen' will cause local impact loadings and restrict headroom.

3.3.6 Signing

Car parks must be adequately signed to help and direct drivers unfamiliar with the area. This helps to avoid congestion and reduces the amount of time and fuel wasted while searching. Where there is a choice of car parks, signs should direct drivers to the one most appropriate for their purpose, such as long-stay or short-stay or parking provided in conjunction with a particular event. Consideration could be given to introducing networked, computer-controlled variable message signing (VMS) (see Figs. 3.9 and 3.10), linked to entry and exit, to direct drivers to car parks where spaces are still available. It is essential that the information given by variable message signs is reliable if drivers' confidence and compliance are to be maintained. Direction signs to car parks should not be used to advertise for the benefit of the operator, whether public or private.

A comprehensive system of signing and road marking should be provided within the car park to assist circulation, to achieve the most appropriate search path and to find the quickest exit. Where several search paths are available, it may be helpful to indicate which levels have vacant spaces.

It has been found that standard highway signs are not suitable for car parks. In consequence, several systems of internally illuminated signs have been developed, clearly conveying their message in words and symbols. Because of the limited headroom common in car parks, signs should be carefully sited to ensure they do not reduce headroom and are not obstructed either by structural elements or by vehicle or pedestrian movements.

Road markings may be similar to those of standard highway design, but will be of little value if not maintained, kept clean and well lit. Internal floors should therefore be cleaned regularly to avoid the accumulation of rubber worn from car tyres and other dust and debris.

The layout of the internal lighting can also be used to guide the motorist. For example, if fluorescent fittings are generally arranged parallel to the parking aisles, a fitting at right-angles to the aisle will help draw attention to a ramp position.

Internally illuminated signs are usual in car parks and are of considerable value in operation and control.

3.3.7 Vehicle safety barriers

A key aspect of vehicle control within a car park is the restraint of vehicles that get out of control. The driver's foot may slip or brakes fail or they may be taken ill at the wheel. In such cases, the car might be driven at high speed into other parked cars or the perimeter balustrade. As a result, high standards of design and maintenance (see Chapter 11) are necessary for perimeter barriers (see Fig. 3.11), with care being taken to ensure that external cladding is adequately protected. For further details of vehicle constraint, see Section 5.6. Columns must be designed to accommodate loading from the vehicle safety barriers where there is insufficient space for fully separated support systems.

3.3.8 Payment systems

The selection of the appropriate payment system will be influenced by the location, function and layout of the car park. It must be considered as an integral part of the design concept.

The requirements are clearly not the same in all car parks and will be greatly influenced, for example, by the nature of the parking demand in the area. In a shoppers' car park, a variable tariff will usually be needed to favour short-stay parking and encourage rapid turn-round. A commuters' car park, on the other hand, may well be operated more effectively on a fixed-charge basis. Other considerations such as the state of congestion of the surrounding highways and queuing space restrictions within and outside the car park may also be important.

The problems of fee collection are far fewer when parking charges do not vary with the length of time that the vehicles are parked. However, a variable tariff enables control to be exercised on the type of parking. Unfortunately, variable-charge tariffs are the most difficult to operate and require extensive and detailed control for their effective operation.

Various payment systems are in common use, including:

- *Fixed charge* – where payment of a fixed charge is made to a cashier or via an automatic machine on entering or exiting the car park.
- *Pay on exit* – where a ticket is issued on entry and payment is made to a cashier or automatic machine on exit, according to the scale of charges geared to the time spent. With automatic machines, serious congestion can develop if a driver does not have the correct change or the system breaks down. Some equipment allows payment by an electronic device, such as a stored-value smart card.
- *Pay and display* – where, after a space has been found, a ticket is purchased from a machine in the car park and displayed on the vehicle. This system eliminates delays at the entrances and exits but, where parking is permitted for more than one fixed period, the driver must decide how much time to purchase before leaving the vehicle. A Traffic Regulation Order is required to enable those drivers who do not pay the correct charge to be fined and, if necessary, prosecuted. The system is often criticised because it penalises drivers who may genuinely have misjudged their length of stay.
- *Pay on foot* – where a ticket is issued on entry and payment is made on departure to a cashier or via an automatic machine before the driver returns to the vehicle.

Whichever system is used, payment facilities should be clearly signed and recognisable and accessible (see Figs. 3.12, 3.13 and 3.14). Credit cards and decrementing cards are being used more and more for payment, to speed things up. In future, it is likely that more sophisticated techniques – such

Fig 3.11 Mixed steel and concrete vehicle edge restraints, respectively fronting lightweight pedestrian restraints and masonry cladding

Fig 3.12 Example of payment facility at Dublin airport

Fig 3.13 Example of payment facility at New World Square car park, Cannons Marsh, Bristol

Fig 3.14 Example of payment facility at Berthelot car park, Lyons

Fig 3.15 High Street Manchester, showing entry and exit arrangements

as in-car transponders with smart cards, number plate recognition, etc. – will become available.

Parking charges should be clearly displayed at the entrances to car parks along with other information about the terms and conditions of use, such as maximum length of stay, excess charges, and whether disabled badge holders may park free. An 'escape route' should also be provided for drivers who choose, at the last moment, not to enter and pay.

3.3.9 Control of exit

With unrestricted free parking or pay-and-display, there is generally no need for exit control equipment. Lockable gates or other barriers may be required to close the car park when it is out of use but, apart from this, only normal highway traffic control measures would be required. If control is necessary, exit lanes are often controlled by barrier arms (see Fig. 3.15). The capacity of such an exit lane depends on the system of payment, the car-park layout and configuration, and the capacity of the surrounding highway system. Consideration and choice of exit barriers are similar to those for entry (see Section 3.3.2).

As mentioned earlier, exit lanes may be controlled by rising-step barriers instead of lifting-arm barriers (see Section 3.3.2). Although more resistant to vandalism, they should be used in conjunction with a traffic signal to ensure that motorists do not fail to note their existence and status. This type of mechanism can cause severe damage to errant vehicles.

A completely freely flowing exit can be provided if collapsible traffic plates are installed in the roadway. These plates, which are hinged at ground level on their leading edge, are arranged so that they permit free traffic flow in one direction while providing a positive barrier to vehicles travelling in the other. They operate effectively but require frequent maintenance since, although robust, they can be damaged and so fail to provide an effective barrier.

3.3.10 Exit capacities

Estimates of the maximum exit capacities of a single lane are governed by the different payment systems, exit and barrier geometry, staff efficiency, and capacities of the local network. Typical limits under ideal conditions are given in Table 3.3.

Table 3.3 Capacities for exit lanes under ideal conditions

Fee collection system	Capacity (cars/hour)
Ticket on entry and payment at a manned exit	240
Ticket on entry and variable payment to a machine linked to the exit barrier	270
Ticket on entry and operation of the exit barrier by a prepaid ticket or token	400

Note: Unless specific information is available or detailed modelling of the specific location is undertaken, it is recommended the above limits be reduced by 20%.

3.4 Pedestrian control

3.4.1 Introduction

A new car park may affect existing pedestrian routes and there may be a need for replacement or additional footpaths, pedestrian crossings and signing for pedestrian routes.

Within the car park, ticket machines and entrances to lifts and stairways should be demarcated from parking areas. Signs should direct pedestrians to the appropriate exit and each level should be given a unique identity to help drivers to find their cars on their return. Letters or numbers are often used but colour schemes or pictorial signs such as animals or flowers may be easier to remember.

Disabled badge holders should have the most convenient spaces in a car park reserved for their use and ticket machines must be easily accessible to them, unless charges are waived. Care must be taken to ensure that disabled people can leave the car park easily, preferably without having to rely on lifts, as these may occasionally be out of order.

The safety of pedestrians should always be considered, and every car park should be designed with this in mind. While there is fortunately no significant pedestrian accident history in car parks, there are many points of potential conflict between pedestrian and motorists which can be made safer at little cost with careful design.

3.4.2 Pedestrian/vehicle conflict

Proposals have been put forward on various occasions for car parks with segregated pedestrian walkways, so removing the conflict between pedestrian and vehicles. This may give safety benefits but has cost implications. In general, areas requiring special attention are stairs, lift shafts, ramps and aisles.

3.4.3 Stairs and lift shafts

Entrances to stairs and lift shafts must be positioned so that pedestrians approaching and leaving the car park and parking floors are subject to the minimum of risk. Particular care should be taken to provide guardrails to prevent pedestrians from walking in front of incoming vehicles.

3.4.4 Ramps

The split-level arrangement is the most common form of multi-storey car park. Here, the floors are arranged at mezzanine or intermediate levels to reduce the gradient and length of the inter-floor ramps. With split-level car parks, it is often impossible to position the main lift and stair shafts so that there is access from all floor levels. However, to minimise the risk of accidents in a busy car park, use of vehicle ramps by pedestrians should be avoided as far as possible. It is strongly recommended that the layout include separate stair access and ramps for pedestrians (see Fig. 3.16). Such routes must be planned to make provision for disabled users (see Section 3.4.8). For example, in the UK, the *Building Regulations*[3.6, 3.7] give useful guidance for access and facilities for the disabled. Sight lines at the ends of access ramps need particular attention to reduce the risk of accidents at points where conflict between vehicles and vehicle circulation movements or pedestrian movements can occur (see Fig. 3.17).

3.4.5 Aisles

In aisles, pedestrians and motorists have to use the same space. Motorists circulating through the car park and manoeuvring in and out of bays must be a hazard to the pedestrian, but this is clearly not a major problem since accidents in main parking aisles are uncommon. Research has shown that bay markings with short sidelines may encourage motorists to drive further into the bays, in effect increasing aisle width.

Fig 3.16 Separate access for pedestrians at ramps

3.4.6 Lifting-arm and rising-step barriers

Pedestrian routes should be kept well clear of lifting-arm and rising-step barriers. Experience has shown that pedestrians attempting to pass though them are likely to be hit by a descending barrier or may trip over the step barrier.

3.4.7 Lifts

Quality of service is the prime consideration to the car park user. The designer has to consider how to achieve satisfactory quality, in terms of user satisfaction, taking into account all those factors that are not considered or perceived by the user.

Technically, the quality of service is normally defined by the waiting interval (the average time before a lift is available to a potential user) and the 5-minute ratio (the proportion of the total population that the lift system can carry in a 5-minute interval). The first of these criteria is directly valid for car-park lifts, but the second is normally the worst case, based on the requirements for personnel arriving at, say, an office block at the start of work, and is not therefore directly applicable. There can be an anomaly, which is dealt with below.

Often, the population using the lifts in 5 minutes is

Fig 3.17 Parc Croix Rousse showing clear sight lines at ramps

calculated from the maximum rate at which cars can enter the car park and the average occupancy of each car, both factors being determined as part of the traffic study associated with car-park design. However, when the car park is associated with a single building or a building complex such as a shopping precinct, the exodus to the car park at the end of work will constitute the worst case and be akin to the conventional 5-minute ratio. This needs to be taken into account in selecting the appropriate type and size of lift.

Lift groups should be based on a waiting time of 40–60 seconds and a population movement relevant to the particular car-park requirements defined above. Because the total car-park height is kept to a minimum, there is normally little opportunity for lifts to make long flights between stops and so they tend to be selected on the basis of fairly low speeds.

Lift positioning should be suitable for the function of the car park and its structural form. Construction of the lift well should take account of all aspects of safety including ventilation and fire safety, for example the recommendations of BS 5655: Part 6: 1990[3.8] as regards safety provisions for lift wells.

Various regulations apply for operating and maintaining lifts and are often reviewed, generally to make them more stringent. Handover documents must cite the relevant criteria appropriate for the car park and its maintenance.

In selecting lifts, it is common to assume that they carry 80% of the nominal personnel capacity. For a shopping centre car park, it is unlikely that lifts will be capable of carrying more than 50% of capacity. If trolleys are available and able to be used in the car park, even 50% could be optimistic, particularly in small lifts. Door widths must also be adequate for such traffic and one lift at least in each group must be suitable for the disabled.

As a guide, one-person lift capacity is required per $100m^2$ of lettable area for a food supermarket. This means having two 20-person lifts for a $4000m^2$ store (see Fig. 3.18). Of course, the empty trolleys must be returned to the stores which provided them, and trolley collection points should be clearly indicated on each parking level. In addition, staff will be needed to collect these empty trolleys and take them back to the supermarkets. This would normally be done outside peak periods, and the passenger lifts would be used. This may not always be possible, and so other means of returning these empty trolleys, possibly by providing an additional lift, may be necessary.

In more general planning terms, the following points should be taken into account:

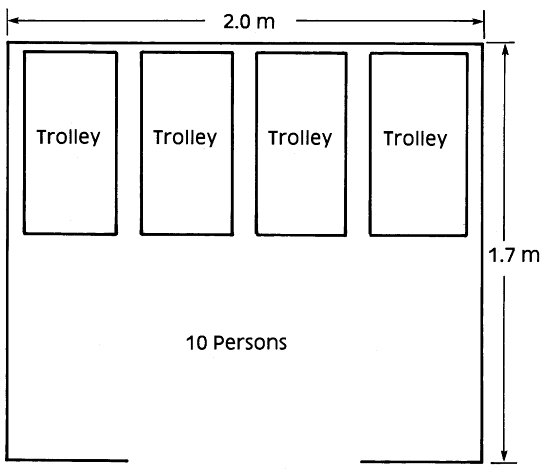

Fig 3.18 Twenty person lift or four supermarket trolleys and ten persons

- Two lifts operating as a group provide a much better service than two single lifts sited in different parts of the car park: the improvement is even more pronounced for four lifts together rather than two groups of two.
- If lift lobbies are provided at every other parking level, suitable ramps must be provided for wheelchairs, prams and trolleys.
- Vandalism can markedly affect quality of service. Adequate provision for servicing, maintenance and emergency callout is a partial answer, but reducing vandalism itself is desirable. Planning that provides better architectural finishes, CCTV and lighting in lift lobbies should be considered (and extended to staircases). Schemes that have a depressing environment and finishes do not discourage potential vandals.
- In the event of fire, either in the car park or in the building(s) with which it is connected, the alarm system should automatically home the lifts to a predetermined floor, leaving them there with the doors open. They should then be controllable only by security staff or the fire authorities. The homing floor should have escape routes to the outside, and it may be a different level depending on whether the fire is in the car park or connected building(s).
- Some alarm facilities should be provided in each lift, so that signals may be relayed to a continuously manned centre in the event of emergencies.
- The need for standby power supplies for emergency lighting in the lift cars and lobbies and for homing the lifts in the event of a power failure should be considered.

3.4.8 Disabled persons

Car-park designs should provide safe access for disabled users. In the UK under the terms of the *Disability Discrimination Act 1995*[3.9], wide powers are available to Local Authorities to require that provisions be made for the disabled. Practical guidance for designers is to be found in *Approved Document M* of the *Building Regulations*[3.6] and in BS 8300[3.10]. In Northern Ireland, *Technical Booklet R*[3.7] of the *Building Regulations (Northern Ireland)* provides guidance.

In general, this means that, when designing lift accessways, ramps should be used as well as steps. In addition, facilities should generally be provided for the movement of wheelchairs. In large structures, emergency refuges may also be required. Furthermore, if public toilets are provided, there should be special provisions for the disabled. It is also good practice to reserve conveniently sited parking bays for the use of disabled drivers. These may be on the ground floor or near lifts or other access points.

References

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3.9 *Disability Discrimination Act 1995*. London: TSO, 1995
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4.1 Introduction

Although a car park is designed to suit the local environment with appropriate linked facilities for pedestrian movement, its use should be seen as an operational 'non-event' to the customer. This means that the designer should consider the full range of operational elements to achieve a comprehensive design solution that results in a safe, easy-to-use, high-quality car park.

This design process is influenced by the parking purpose, how often users visit, payment and control systems, and relationship to the external highway network. Hence, for short-stay parking such as for shoppers – where higher dynamic and turnover capacities are required – wider bays are recommended. However, for office environments and long-stay parking where users are familiar with the parking procedures and turnover is a lot lower, narrower bays could be considered. Similarly, in a small car park, a low dynamic capacity may be acceptable, since at worst few drivers will be inconvenienced and then only for a short period. In a large car park, such a restraint is likely to be unacceptable because of the larger number of drivers affected and the greater delay that would be caused.

For small private car parks, it is sometimes suggested that narrower bays may be used and headroom restricted, lack of circulation capacity being overcome by controlling the circulation and the parking of cars. However, for public car parks, this would give rise to a poor car-parking environment, which could impact on security fears and lead to low usage or crime. It is to be noted that the size of the car is a variable and the current market provides a full range of vehicles including sports, saloons, estates, four-wheel drive (4 × 4s) and multi-person vehicles (MPVs). The car market is not restrictive and so the flexibility of car dimensions has to be considered within the design with particular attention to widths and headroom requirements. The latter are most applicable to 4 × 4s and MPVs, which when fitted with roof bars or boxes can lead to a marked increase in clearance requirements. Any requirements for access for emergency vehicles will fundamentally affect all aspects of car-park design and therefore associated issues require early consideration, especially with respect to access routes.

It is recommended that provisions be made for entrance and exit controls from the inception of planning of a car park. In many instances, for both public and private car parks, entrance and exit controls are required to restrict use to those authorised, to exclude cars when the car park is full, to prevent cars entering by an exit, and to ensure that payment for use is made. The design should also allow for flexibility in the type of controls to be installed since in time it may be necessary to install controls where none is required initially, or to alter those installed as a consequence of changing circumstances. If initial provision is not made for entrance and exit controls, it may later be difficult or impossible to make adequate provision within the site area.

The car park has to provide good pedestrian links to external facilities. The links through the car park will require careful application of the design details with consideration given to footways, crossings, and standing areas adjacent to lifts and doorways. Good visibility with suitable clearances will enable people to move safely through the car park.

Many factors influence whether a user will find the car park easy to use and be comfortable in the car park. The most important elements are outlined below:

- size of car park and ease of circulation
- layout in terms of column spacing, ability to find available spaces easily, aisle and ramp widths, headroom and ramp gradients
- safety and security
- level of visibility
- lighting
- quality and style of internal surface finishes
- clear and concise user information and signage.

This section examines the key elements that control design standards under three headings:

- the car
- geometric requirements
- layout.

The recommendations apply to all classes of multi-storey and underground car park available for public and private use. Special consideration and different standards will apply if the car park is required to provide access routes for large emergency vehicles, e.g. fire engines.

Recommended dimensions in this section are net and allowances should be added for finishes and fittings and the sizes of columns where these protrude into the parking bays. For bays demarcated by lines on floors, dimensions are to the centres of lines.

4.2 The car

A UK review of manufacturers' details[4.1] for new cars available in 1999/2000 identified a change in vehicle characteristics since the second edition of this document. Such vehicle characteristics may vary with time and will depend on the country being considered. In particular, the introduction of MPVs and 4 × 4s has increased headroom requirements. A range of European vehicle dimensions (excluding limousines and extended vehicles) is given in Table 4.1.

The turning circle of a car is not prescribed in the *Road Vehicle (Construction and Use) Regulations*[4.2]. The only prescribed dimension relates to large commercial vehicles able to turn within a circle diameter of 25.0m. The design standards within this document are presented to accommodate the swept paths of the design cars. However, where the designer requires the geometry to be confirmed, computer-generated swept paths should be employed. Current programs include AUTOTRACK and AUTOTURN.

Table 4.1: Comparison of typical vehicle dimensions

Vehicle group	Proportion of vehicle group	Length (m)	Width (m) (Note 1)	Height (m) (Note 2)
Small car	95%	3.95	1.75	1.75
Standard car	95%	4.75	2.06	1.85
Large car	100%	5.40	2.24	2.05
MPVs	100%	5.10	2.20	1.90
4 × 4	100%	5.05	2.25	2.05

Notes: 1. Width including wing mirrors.
2. Height excluding roof boxes, racks and roof bars

Turning circles can range from 10.2m for a typical small car to 12.62m for a Rolls-Royce; for larger limousines it could be up to 15.0m. These are minimum kerb-to-kerb turning circles and do not include body overhangs and driver ability. Hence, practical turning circle diameters for large cars could range from 13.4m to 15.0m. A simple template of a large car is shown in Fig. 4.1.

The examination of new cars available in the UK[4.1] shows that the height of 95% of standard cars fall below 1.85m, exclusive of roof racks/box. However, for MPVs and 4 × 4s, the 95 percentile increases to 2.05m. Adding a roof box increases the 95 percentile vehicle height to some 2.35m and 2.55m respectively.

4.3 Geometric requirements

Parking arrangements should be designed to allow drivers to manoeuvre easily and safely and, where appropriate, to segregate vehicles from pedestrian areas and routes. The manoeuvring ease is a function of aisle and bay widths, which also influence the dynamic capacity of the car park. This is of particular importance for short-stay car parks such as at retail centres where aisle capacities are critical to the operation car park. For longer-stay car parks, this is not so critical; therefore the bay dimensions could be reduced where customers are more familiar with the parking arrangements such as at office or station car parks.

4.3.1 Bay width and length

Recommended practice is to design for normal use by the standard car and for occasional use by the large car. However, consideration needs to be given to the requirements of specialist car parks, and to increased vehicle dimensions. Increased headrooms may be applicable to car parks located in tourist areas where a greater proportion of vehicles with roof boxes are likely. Typical bay dimensions for standard cars are shown in Table 4.2.

4.3.2 Aisle width and bin width

Guidance for aisle and bin widths for various parking angles with bays on each side are shown in Table 4.3. These preferred dimensions are clear of any structure or edge details (but see Sections 4.3.3. and 4.3.4). Aisle widths are designed to accommodate any overhang of vehicles beyond 4.8m. To suit constraints imposed by limited space or particular user operations, variations to these dimensions can be considered. Where this results in reduced dimensions, the client should be made aware of the variations and the resulting limitations such as restricted space between parked vehicles and more difficult manoeuvring. Where comfort parking conditions are required, as in retail parks, operators often specify greater dimensions.

Although they increase the dynamic capacity of an aisle, parking angles of less than 90° are little used in underground and multi-storey car parks, as the space requirement per bay increases and cost efficiency is reduced. As a general guide, 45° car parking reduces the total parking space by some 20% compared with 90° parking. Hence, the parking angles and associated aisle widths are provided for guidance, and circumstances may justify using different widths.

4.3.3 Side clearance on structure

Widths of end parking bays should be increased where they are adjacent to walls or vehicle barriers. This increase will be subject to the edge detail form, but an additional side clearance of some 300mm is suggested from the bay marking to the edge detail.

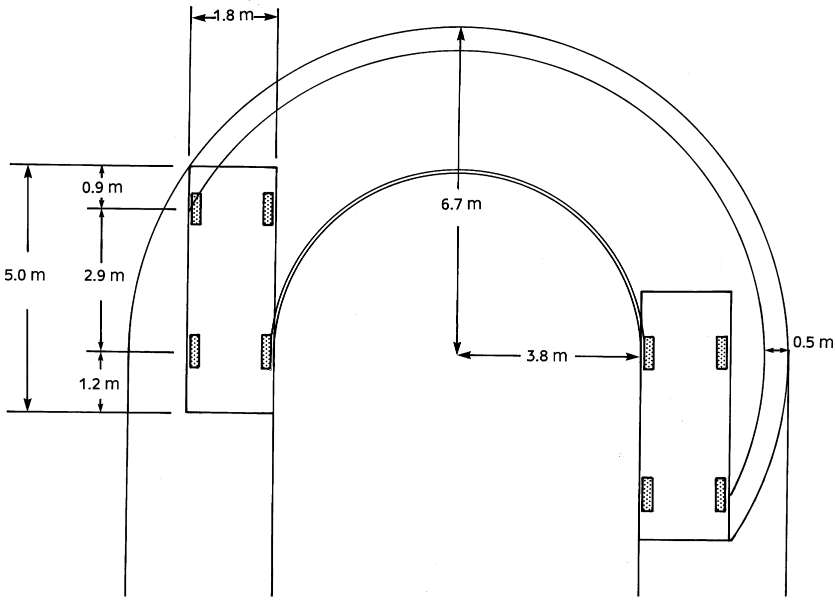

Fig 4.1 Swept path of a large saloon car

Table 4.2 Car bay dimensions (Note 1)

Type of parking	Length (m) (Note 2)	Width (m)	Comment
Mixed use	4.80	2.40	Mixed occupancy
Short stay	4.80	2.50	Typically less than 2 hours
Long stay	4.80	2.30	One movement per day e.g. business car park
Disabled user	4.80	3.60 (Note 3)	
Parent/child	4.80	3.20 (Note 4)	

Notes:
1. The dimensions are to be clear of any projections, but see Section 4.3.4
2. The preferred dimension is 4.80m for all bay lengths. However, with restricted space and appropriate signage, this can sometimes be reduced for small vehicles (see Section 4.4.1)
3. The bay width for use by disabled persons allows for the door to be fully opened to improve movement in and out of the car and to provide greater room for assistance to be given to those less mobile. Additional details are given in Traffic Advisory Leaflet 5/95[4.3] *Parking for Disabled* and *Building Regulations* [4.4, 4.5] for facilities within and around buildings
4. The bay width for use by parent and child allows for the door to be opened more fully for access to child seats.

Table 4.3: Recommended aisle and bin widths

Parking angle	Preferred aisle width (m)	Bay width (m)	Preferred bin width (bay length 4.80m)
90°	Two-way aisle 6.95	All	16.55
90°	One-way aisle 6.00	All	15.60
60°	4.20	2.30 2.40 2.50	14.85 14.95 15.05
45°	3.60	2.30 2.40 2.50	13.65 13.80 13.95

4.3.4 Column location

Clear-span construction is preferred, as it provides a safer environment for both drivers and pedestrians, but other design considerations often dictate the use of internal columns. The sizing of these columns and the spacing has to be carefully considered to maintain parking efficiency, bay access and sight lines. Columns at the front of the bays can reduce accessibility. Therefore, to improve parking manoeuvres, the recommended distances of columns from the aisle are shown in Fig. 4.2.

It is recommended that no fewer than three standard bays are provided between interbin columns adjacent to aisles and that bay widths be clear of finished column faces. However, a projection of 150mm to 200mm is acceptable if columns are within the recommended setback zone from the aisle (see Fig. 4.2). Where larger columns are provided, as in mixed-use developments, special attention is required to maintain satisfactory clearances and operations. In such cases, the co-ordination of building and car park grids will need to be an iterative process.

It is also to be noted that columns within the mid-third of the bay will obstruct doors and should be considered carefully, especially where shear walls are being proposed. Additional side clearances will be required with shear walls.

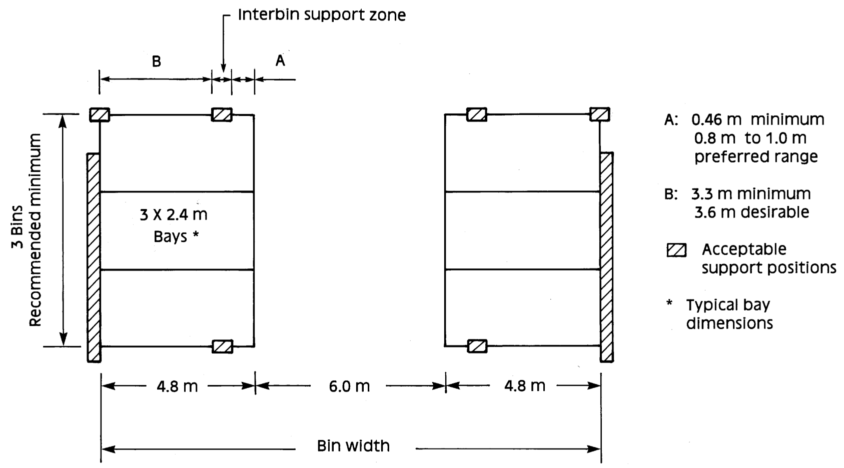

Fig 4.2 Support positions related to parking geometry

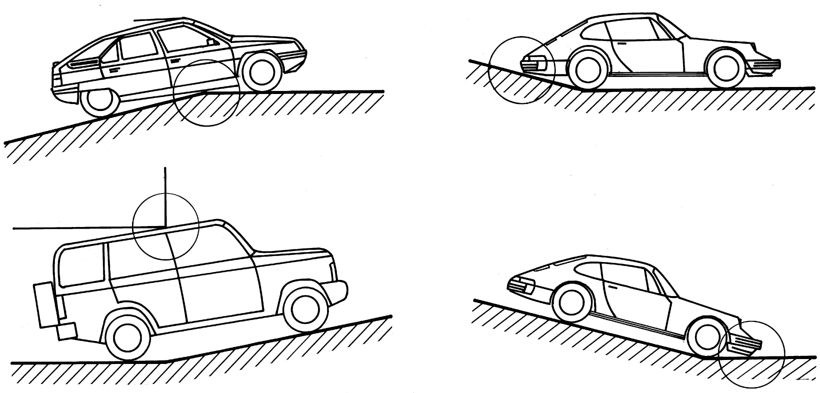

Fig. 4.3 Possible points of damage to vehicles

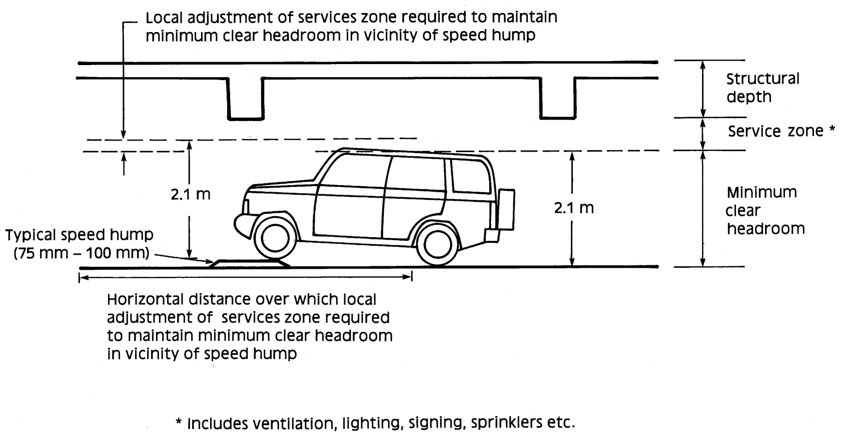

Fig 4.4 Headroom allowances

4.3.5 Headroom

The recommended minimum clear height or headroom, measured normal to surfaces, for vehicles is 2.10m. This minimum is applied to entrances, exits, bays, aisles and ramps and so careful attention needs to be given to the various requirements applicable to each area. Additional clearances will be needed at changes in gradient such as at ramps and where traffic-calming measures are used (see Fig. 4.3).

To determine structural height, it is recommended that outline designs be prepared for signage, lighting, ventilation, barrier controls, sprinkler system and any other possible projections below structure such as conduits and drainage pipes. The downward projections of these various services should be estimated and added to the headroom to determine the clear structural height required. In addition, allowance should be made for finishes, dimensional tolerances and structural deflections. It is recommended that the headroom be checked at the bottom of ramps since cars will span from ramp to floor.

Traffic-calming measures such as speed humps and tables, must be carefully located. These measures are typically 75mm to 100mm high and so will restrict headroom locally. Where rising-step traffic control is proposed, pits 300mm to 600mm deep may be required. This local increase in depth must be taken into account when considering the available headroom on the floors below. Headroom allowances relating to structural depth and the depths for services and 'sleeping policemen' are shown in Fig. 4.4.

For safety, the headroom indicator board at the entrance to the car park is normally set some 50mm to 100mm below the actual headroom within the car park. Hence, the operational headroom could be set below the minimum clear floor height in the clients' brief. This needs to be taken into account, discussed and clarified with the eventual operator.

The minimum headroom of 2.10m will generally cater for all MPVs and 4 × 4s (without roof boxes) as long as allowance is made for transitions on ramps, particularly in split-level car parks where a maximum gradient of 1:6 is frequently applied. Examples of these headroom design elements are given in Figs 4.3, 4.5 and 4.6.

Where provision is required for designated spaces for high top conversion vehicles, e.g. those for disabled people, a minimum clearance of 2.60m is recommended[4.6] for the full access route in lieu of the normal minimum headroom of 2.10m. If sufficient vertical clearance for high-top conversion vehicles can not be maintained along all routes in the car park, drivers should be warned about the height restrictions before they begin to queue for or enter such areas. At that point, there should be directions to a suitable alternative parking space.

4.3.6 Floor gradient

Floors should be laid to a fall of 1:60 for drainage.

Deflections of long-span beams can also affect the gradient required to maintain drainage falls (see Section 5.5.1 and Chapter 9). Where continuous parking deck ramps are considered, the recommended maximum gradient is 1:20. Where parking ramps are steeper than 1:20, difficulties may be experienced in opening and in keeping open a car door on the up-gradient side and in closing a door on the down-gradient side. In addition, shopping trolleys may roll away, and those with impaired mobility could experience problems. Flatter gradients are therefore preferable. In motorcycle parking bays, gradients should be arranged to avoid crossfalls.

4.3.7 Ramp and accessway gradients

The recommended maximum gradients for vehicle ramps are given in Table 4.4.

If ramps are steeper than 1:10 or the floor is laid to a fall of 1:60 or greater away from the ramp, a transition length is required. These transition gradients should be sited at the top and bottom to reduce the risk of vehicle grounding. The transition length should be at least 3.00m and its gradient half the gradient of the ramp. This transition can extend into the circulation aisle with appropriate blending of grades.

Pedestrians (particularly with push chairs) will often use vehicle ramps within a car park but this is of some concern, as pedestrian safety is compromised. The vehicle ramps are usually of a gradient between 1:6 and 1:10, which are unsuitable for disabled people, for whom guidelines require the steepest permissible to be 1:12. It is recommended that separate pedestrian routes be provided, ideally with gradients between 1:15 and 1:20 with level landings every 10m. Full details are presented in supporting documents to *The Building Regulations*[4.4, 4.5].

4.3.8 Ramp and accessway curvature, widths and clearance on structure

The recommended outer kerb radii for one way curved ramps are shown in Table 4.5.

The turning circle of the large design car can be between 12.00 and 15.00m diameter between kerbs. In consequence, if the proportion of large cars using a car park is expected to be above average, it is recommended that curved ramps and accessways have an outer kerb radius of not less than 9.00m. A typical two-way spiral ramp is shown on Fig. 4.7. The recommended minimum widths for curved ramps are shown in Table 4.6.

On long straight ramps, the recommended width between kerbs is 3.00m. However, where cars turn on entering or leaving a straight ramp, a widening or flare is usually required at the ramp ends. The amount of flare required depends on the ramp width and the approach and exit manoeuvre at the top and bottom of the ramp. Clear sight lines are valuable in these locations. For a split-level car park with a short ramp, a constant ramp width of 3.50m is more appropriate (see Fig. 4.8). Table 4.7 gives the recommended minimum widths for one-way straight ramps and accessways.

4.3.9 Superelevation

Curved ramps should have superelevation: the recommended maximum provision is 1:20.

4.3.10 Kerb height

Any kerbs within the car park need careful consideration, especially as regards the fixing detail and its interface with deck waterproofing. As kerb details often lead to maintenance concerns, kerbs should be omitted from parking

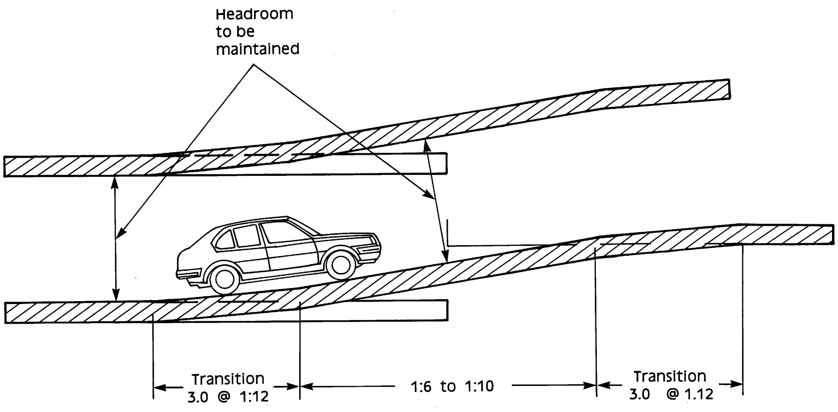

Fig 4.5 Typical ramp elevation

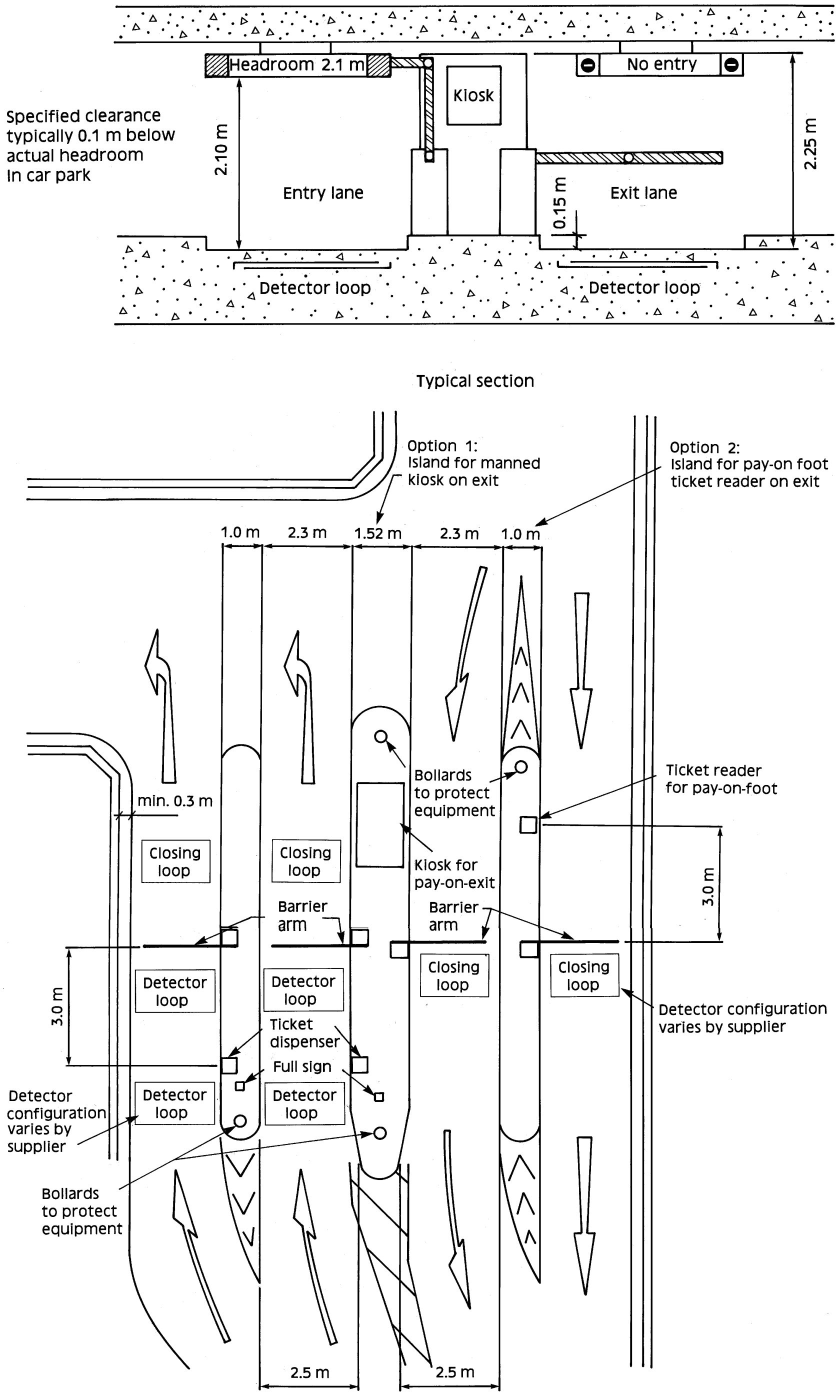

Fig 4.6 Layout of entry/exit controls

Table 4.4 Maximum gradients for vehicle ramps

Ramp type	Rise	Maximum gradient
Straight ramps	not greater than 1.50m	1:6 (Note 1)
	greater than 1.50m	1:10
Curved ramps (Note 2)	not greater than 3.00m	1:10
	greater than 3.00m	1:12

Notes: 1. With transition gradients top and bottom
2. Gradient measured on centre-line

Table 4.5 Recommended outer kerb radii for one-way curved ramps

Option	Radius (m)	Structure clearance outside kerb (m)	Structure clearance inside kerb (m)
Recommended	12.00	0.60	0.30
Preferred minimum	9.00		
Absolute minimum	7.50		

Table 4.6 Recommended minimum widths for curved ramps and accessways

Ramp type	Ramp width (m)	Width of additional central raised kerb (m)	Structure clearance outside kerb (m)	Structure clearance inside kerb (m)
One-way	3.65	N/A	0.60	0.30
Two-way	7.00 (Note 2)	0.50		

Notes: 1. See Fig.4.7
2. For two-way ramps a central raised kerb of 0.5m is recommended

Table 4.7 Recommended minimum widths for one-way straight ramps and accessways

Ramp type	Position	Width (m)	Additional side clearance to structure (m)
One-way (Note 1)	Width for straight approach	3.00	0.30
	Entry/exit section for turning approach	3.50	

Note 1: For two-way ramps a central raised kerb of 0.5m is recommended.

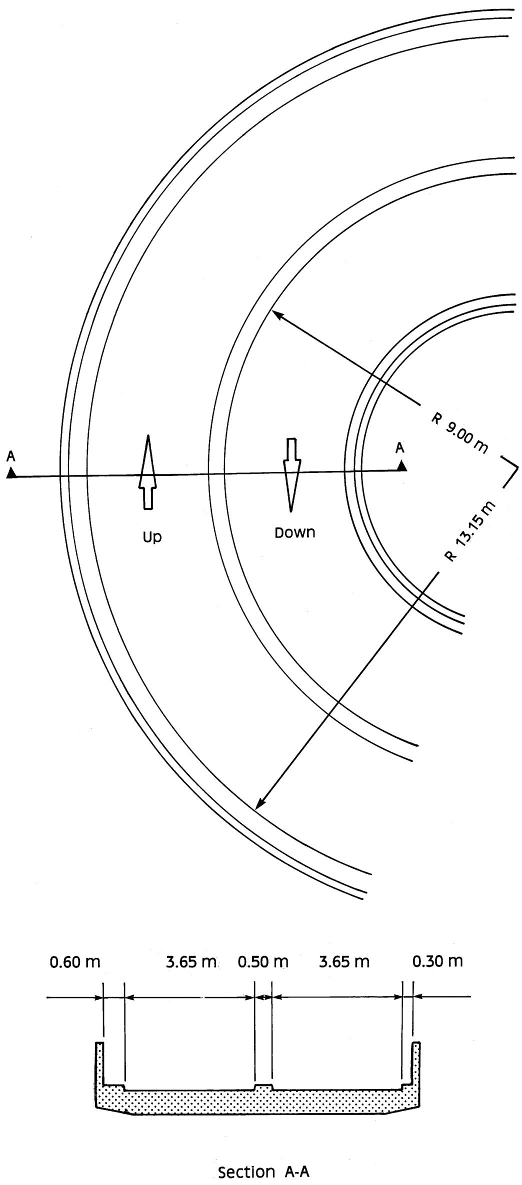

Fig 4.7 Two-way spiral ramp

levels wherever possible. On ramps, kerbs are considered essential to guide drivers and to protect edge details and equipment. The use of central kerbs on ramps to separate opposite flows of traffic is not generally recommended as drivers on the falling ramp find the kerb difficult to see and the kerb could unnecessarily restrict the movement of vehicles.

When it is important that cars do not mount kerbs, the recommended kerb height is 150mm above channel level; in other cases the kerb height should not exceed 100mm. The disabled and parents with pushchairs should be accommodated by providing drop kerbs on designated routes.

4.3.11 Entry and exit arrangements

To prevent queuing at the point of entry, the entry capacity should be equal to, or greater than, the maximum expected arrival rate. Vehicle reservoirs are required between the public road system and the entrance barriers to store vehicles during peak operations and provide a transition from the higher speed external highway network to the slower access road configuration. The rate of flow from the car park should respect the highway and junction capacity, so that any queuing takes place off the highway. However, as it is likely that queuing will occur at peak exit times, facilities should be allowed for queuing within the car park on each side of the barriers.

It may sometimes be appropriate to provide a facility for vehicles to escape the car park system before passing the barrier line on entry. Where required suitable turning arrangements will need to be accommodated.

It may also be advantageous to site the entrance and exit side by side, with one or more lanes made reversible. Then, if peak inbound and outbound demands occur at different times, a lane or lanes may be reversed as appropriate.

The entry and exit lanes within these reservoirs are typically 2.75–3.0m wide. However, if this width is maintained adjacent to ticket issue and reader machines, or at payment stations, drivers will experience difficulties as they may not be able to reach the machinery or kiosk. This will reduce the dynamic capacity of the system as drivers lean out of the windows, open doors, or even get out of their vehicle to use the machine. Hence, drivers should be encouraged to approach ticket machines and payment stations as closely as possible by restricting the width of the lanes adjacent to control equipment to 2.30m. A typical gate layout is shown in Fig. 4.6. Selection of rising-step barriers has implications to the structural form and headroom (see Section 4.3.5).

Where approach and exit routes of control systems are on bends, the swept paths of the vehicles should be checked and lanes widened if need be. Positioning entry or exit controls on bends is not recommended. Access lanes to control equipment should provide generous space for drivers to manoeuvre cars into position for easy operation of the equipment from within the car. Where space allows, it is recommended that a straight of at least 6.00m be provided on the approach to control equipment. In addition, the area alongside the equipment should have shallow gradients to reduce braking and starting difficulties. Gradients between 1:20 and 1:40 are desirable.

The design of the lane layout near the entry and exit controls should consider the consequences of equipment or vehicle failure. This could include providing duplicate machines, additional lanes, ability to bypass failed cars or machines, or vehicle waiting areas before the control systems. Actual requirements will depend on individual circumstances, including the provision made by manufacturers in equipment to reduce malfunctioning. However, these facilities will help minimise the potential disruption to the throughput of vehicles.

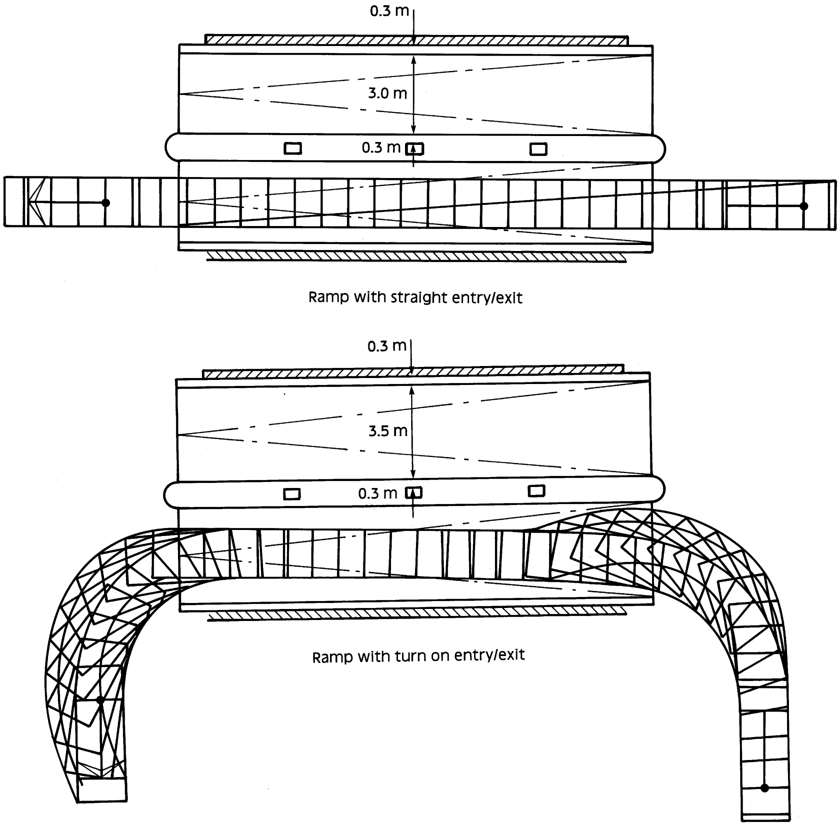

Fig 4.8 Ramp widths and clearances

Fig 4.9 Example of typical car park layout

4.4 Car park layout

4.4.1 Principles

The car park design has to carefully consider the customer and provide a system that is easy and safe to use. It must also be compatible with the locality and follow the guidelines established by the Local Planning Authority in terms of appearance and scale. These principles of use and planning tend to control the size of the car-park system, the circulation facilities, and application of the geometric design requirements (see Fig. 4.9).

Short-stay operations, such as facilities associated with retail centres, will have a greater turnover for a given level of static capacity and so will attract more two-way traffic throughout the day. Long-stay facilities associated with large office or business complexes and railway stations will produce high single-direction traffic flows in the mornings and evenings. Car parks expected to carry considerable traffic flows throughout the day or under tidal conditions should preferably have one-way-only systems, which give increased dynamic capacities.

Drivers free to use any bay will want to park as close as possible to their destination. At car parks where this nearest level is also close to the control gates, this desire can quickly create entry system congestion especially during busy periods while arriving drivers wait for others to move out. Examples of this are the car park floor closest to the shopping mall level, the cinema, or other leisure operations. This can therefore give a false impression of the static efficiency, as excessive congestion being noted on the first levels of the car park, at the control gates, and on the external network, while the parking levels further away can be nearly empty. Careful planning of ramps and exit locations can overcome this by allowing rapid search routes, taking customers to other levels without the need to circulate each level.

In large tidal flow car parks and short-stay facilities, provision should be made to short-circuit the car park with a rapid ‘up’ route and, if necessary, a rapid ‘down’ route. Search paths for incoming drivers should not generally involve more than 500 bays (see Section 4.4.7).

The maximum practical occupancy will probably be lower than the theoretical static capacity owing to a number of factors. Not all drivers will park in the first vacant bay, parking discipline may be poor, and those already in the car

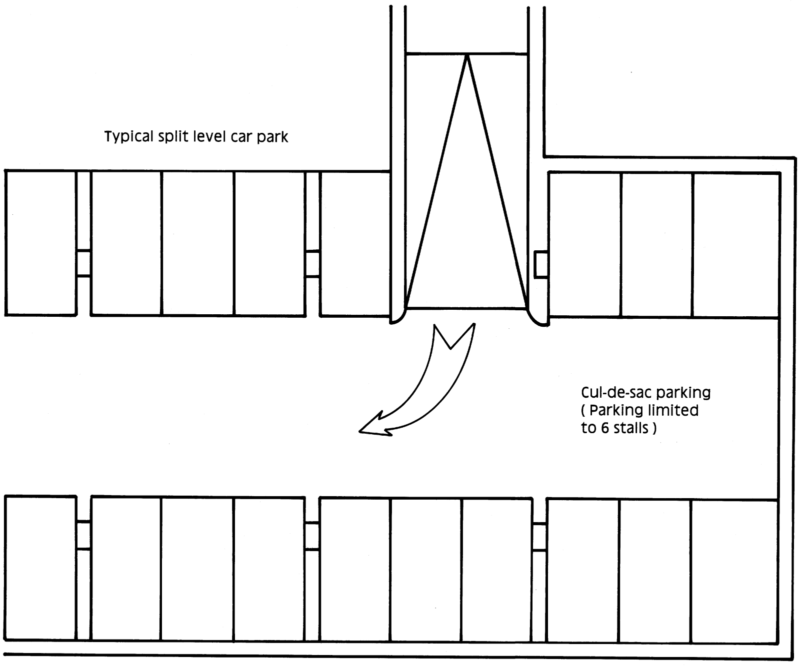

Fig 4.10 Cul-de-sac arrangement with larger end bays

park may miss vacated spaces. Therefore, where entry is controlled, deliberate under-capacity margins of about 5% are sometimes introduced. In addition, to enhance static and dynamic efficiencies, re-circulation to the various car park levels should be possible without drivers having to leave the car park.

The size of the car park is guided by:

- the adequacy of the dynamic and static capacity
- the length of the search paths
- the ability to short-circuit levels by rapid ramp systems
- planning guidelines.

In European standards, a proportion of parking spaces can often be smaller to reflect local predominance of the small-car market. If this is a general trend, small car bays of 4.00m by 2.20m could become more acceptable as a standard within UK car parks. Another area of variation relates to the aisle width. For 90° parking this can be reduced to some 5.50m providing that the bay width is at least 2.50m.

These variations in design geometry clearly identify the challenge for the designer, who has to balance users' requirements and Planning Authority Standards against the clients' brief.

In the USA, larger vehicles and other standards apply[4.7]. Accordingly, design parameters will have to be reviewed and further research undertaken.

If cycle and motorcycle bays are required, they should have an up-hill entry gradient and minimum cross-fall. They are preferably located on the car park entry level.

Where parking facilities have to accommodate high vehicles, e.g. those for disabled persons, the first floor could be designed with greater headroom (see Section 4.3.5). In such cases, additional height restriction warnings and measures will be required to prevent movements into areas with lower headroom.

4.4.2 Cul-de-sac parking

As bays within cul-de-sacs (see Fig. 4.10) are generally off a driver's search path, it is preferable to avoid multiple cul-de-sac aisles. If they are used, the maximum cul-de-sac capacity should be six bays. Manoeuvring into and out of the end bays can be especially difficult and so larger bays are usually necessary which leads to less efficient use of space.

4.4.3 One- and two-way aisles

Drivers want to be able to find their way around the car park easily so that they can concentrate on looking for a vacant space. Cross movements should be avoided and aisle widths should be suitably sized. One-way circulatory systems and aisles, which normally have a higher dynamic capacity than two-way systems, can do much to reduce confusion and congestion.

Drivers sometimes disregard one-way operations, leading to flow disruption and perhaps a safety hazard. This can be managed by good signing and lane markings. However, if two-way movements are considered likely, two-way aisles should be introduced. This will require wider aisles and better visibility along with the correct markings and signing. Although this problem is more applicable to surface-level facilities, it should be borne in mind.

4.4.4 Parking angle

Placing bays at an angle of less than 90° is a convenience for drivers since it facilitates entry and exit. This in turn improves the 'dynamic and turnover capacity' of the aisle. However, a disadvantage is that greater floor area per car is required. This reduction in 'static efficiency' – namely the ratio of area provided in bays to the total floor area – can significantly increase the cost per space. For standard bay dimensions and one-way aisle operations, reductions in the order of 3% can be expected for angles from 90° to 70°. For 45° parking, this reduction can be about 20%.

4.4.5 Parking-area layout

Parking-area layouts may be classed as:

- flat deck
- split level
- ramped floor
- warped slab.

The principles of layouts are reviewed here:

Flat-deck layout (see Fig. 4.11). Each deck is flat. The decks are linked by ramps, the illustration showing external curved ramps. Straight ramps may be used, in which case they are usually internal. Flat-deck car parks are normally built in multiples of a bin width, but the layout is adaptable. In Fig. 4.7, the ramp circulation is anticlockwise to suit the entrance and exit arrangements. In the UK, a clockwise circulation is preferred, that is with the driver on the inside of the turn. This is not regarded as essential.

Split-level layout (see Figs. 4.12, 4.13 and 4.14). The illustrations operate with drivers entering by the up ramp system and leaving by the down ramp. In an underground car park, the same principles apply but the ramps reverse; the down ramp system becomes the entry ramp. The parking levels are flat decks or levels. The rise between levels is half the floor-to-floor height. Since the rise between levels is usually 1.50m or less, the ramps may be at 1:6. This class of car park is commonly built with up to 12 levels, inclusive of the ground levels. It is usual for aisles to be one way since they are part of the ramp circulation, which is one-way. The

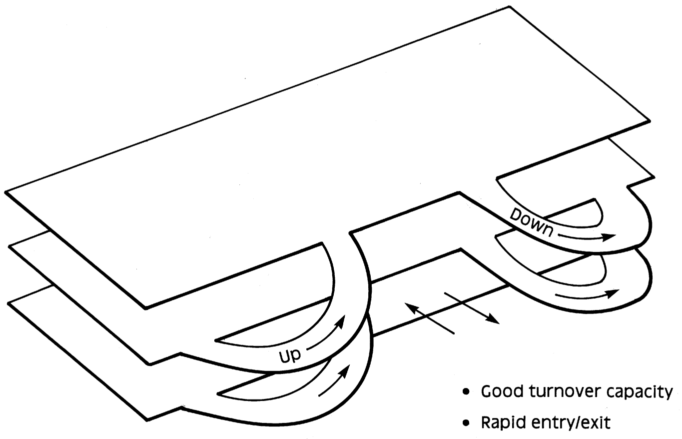

Fig 4.11 Flat deck car park with external ramps

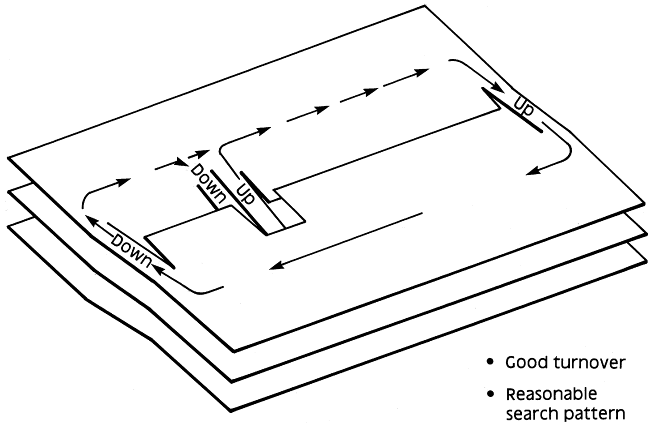

Fig 4.13 Split level car park with separate entry and exit circulation and with short down (exit) ramp system

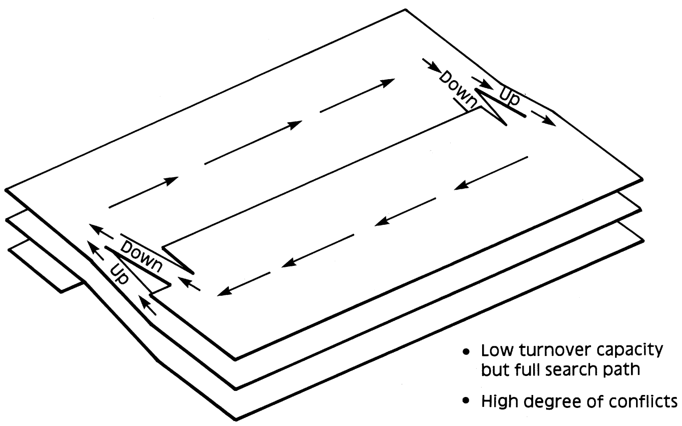

Fig 4.12 Split level car park with combined entry and exit circulation and with end ramps

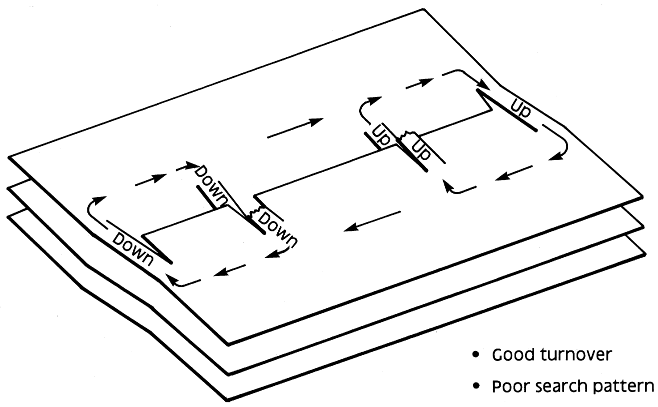

Fig 4.14 Split level car park with separate entry and exit circulation and with short up (entry) and down (exit) ramp systems

usual widths of the levels are a bin or multiples of a bin but may be adapted to a site.

In Fig. 4.12, the up-and-down ramps are at the ends of the structure. The scissor arrangement of the up-and-down ramps has a low dynamic capacity because sight distances are short where traffic streams merge. As shown in Fig. 4.12, the departure route is long.

In Fig. 4.13, the up-and-down ramp systems have been separated. The down-ramp system is short, and the up- (or entry-) ramp system in principle includes the remaining bays.

Fig. 4.14 illustrates the use of a short up-entry-ramp system as well as a short down-ramp system.

Attractions of the split-level layout are its compactness, that the ramp system is internal and that the space taken up by the ramps is a minimum. It may be difficult to search systematically for a vacant bay. In car parks laid out on the lines of Figs. 4.13 and 4.14, a driver may see a vacant bay that cannot be reached, if the one-way aisle system is observed, without first going up a level and then down a level. Similarly, when leaving from some bays, it is necessary first to go up a level. Lifts and stairs should access all levels to avoid pedestrians needing to use vehicle ramps. Particular care is required in the design of details to provide adequate visibility and clearance at overhangs (see Fig. 4.15).

Ramped floor layouts (see Figs. 4.16, 4.17 and 4.18). Cars are parked off an aisle, which also acts as a ramp. The ramp may be two-way.

Fig. 4.16 shows a one-way aisle system with a clearway down (departure) ramp. Since there is a single search path, this layout is not recommended for a capacity of more than 500 bays: even then, the search path may be found inconveniently long. Instead of a clearway departure ramp, a departure parking ramp may be used.

In Fig. 4.17, the down parking ramp is end-to-end with the up parking ramp.

In Fig. 4.18, the up-and-down parking ramps are interlaced. The view has been exploded to show all ramps.

Ramped floor car parks are usually built two bins wide, and the layout is not adaptable to a site. The ramp need not be laid out as in the illustrations: it may, for instance, be laid out as an oval or a square. Ramped-floor car parks with steep gradients should be avoided as it may be found difficult to open or hold open a car door on the up-gradient side and to close a door on the down-gradient side.

Warped-slab layout (see Fig. 4.19). At the edges, floor slabs are flat. Internally, floors are built to falls to provide an internal ramp system. It is usual for aisles to be one-way. The layout is adaptable in the same way as the flat-deck layout. A factor that should be considered with the warped-slab layout is that the maximum gradient occurs on the central crossover. With a car parked in this area, it may be difficult to open or

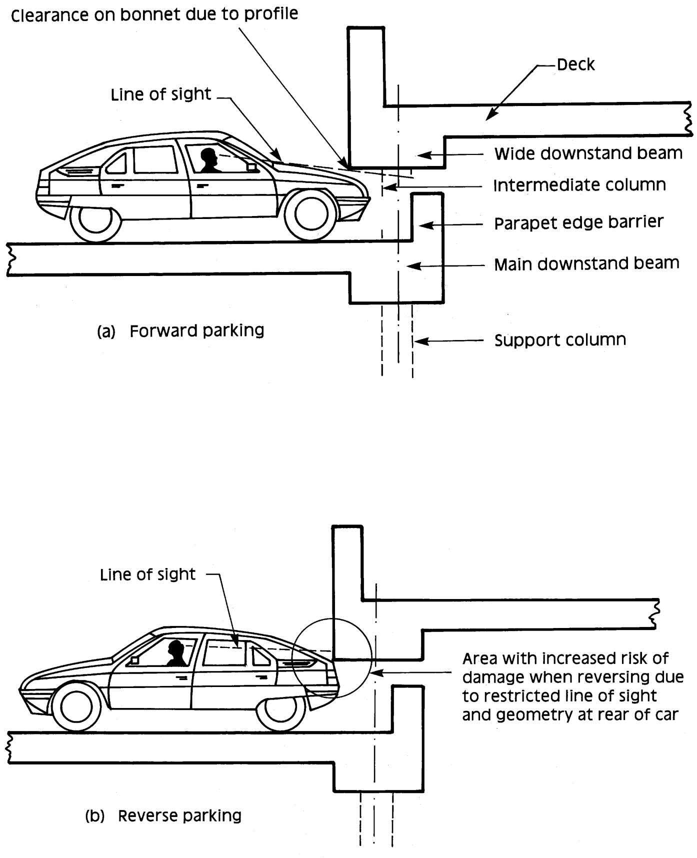

Fig 4.15 Clearance and visibility issues around downstand beams

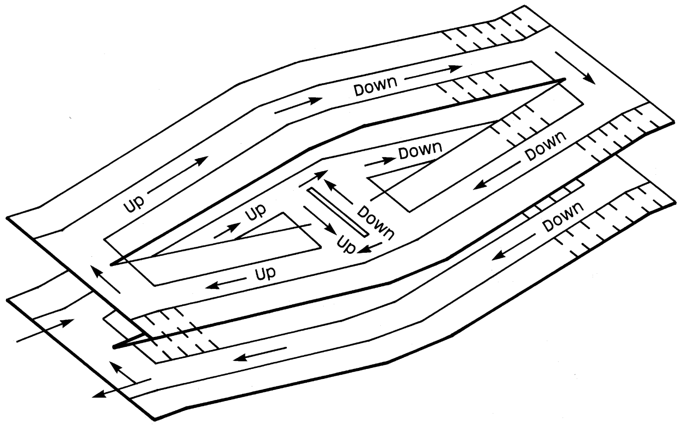

Fig 4.17 Ramped floor car park with separate entry and departure parking ramps

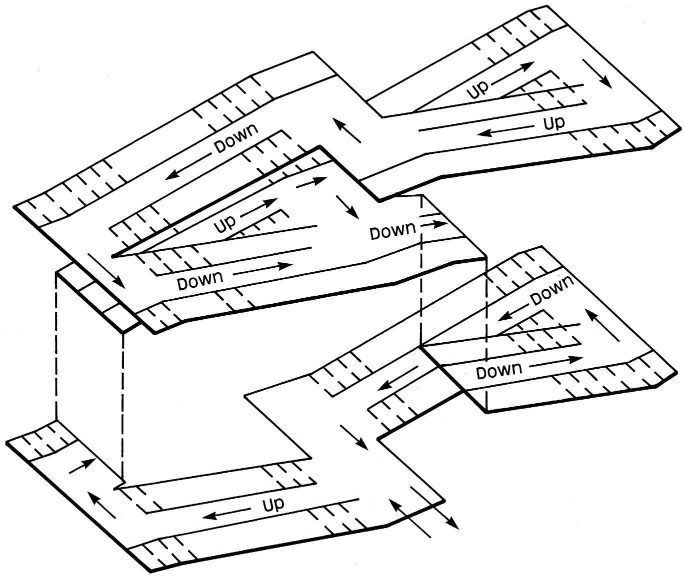

Fig 4.18 Ramped floor car park with interlaced entry and departure parking ramps

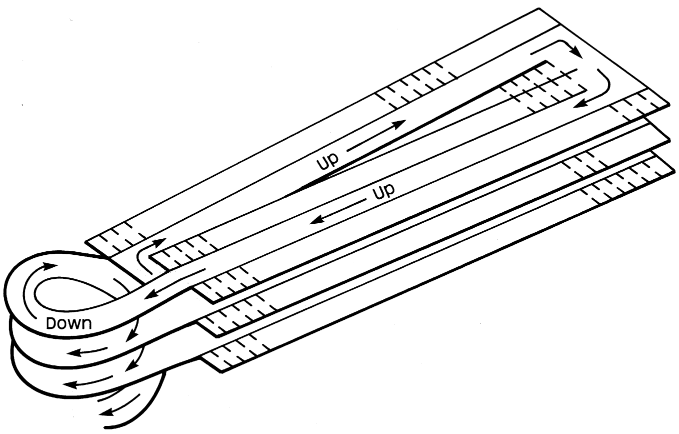

Fig 4.16 Ramped floor car park with a clearway down (departure) ramp

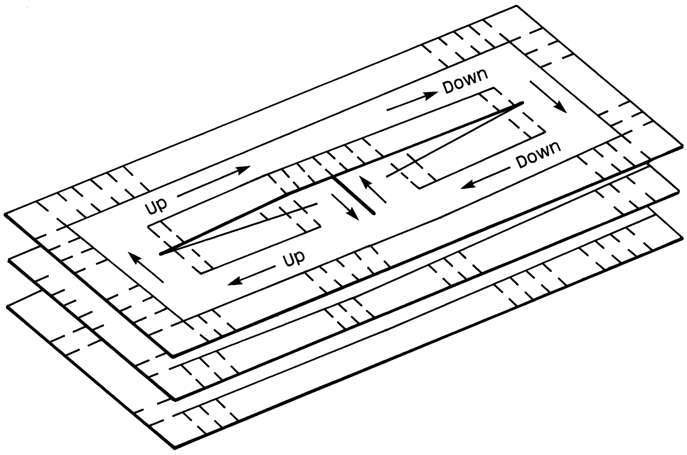

Fig 4.19 Warped slab car park

hold open a car door on the up-gradient side and to close a door on the down-gradient side.

4.4.6 Ramps

Ramps are required to give access to parking levels. In a car park with three or more parking levels, access to those levels may involve the use of aisles (as with split-level car parks), or the layout may not require drivers to route through aisles. A clearway ramp is a ramp system that does not include aisles. Ramps may be straight or helical (circular in plan).

Clearway ramps are used when it is desired to speed access time, to avoid through-traffic in parking areas, or where a ramp aisle system has insufficient dynamic capacity. If only one clearway ramp is provided, it is usually the departure ramp.

Failure to design to an adequate standard will reduce capacity and can increase the accident risk.

In some layouts, traffic contraflow occurs on straight ramps or crossovers between ramps. In these unusual cases, it is recommended that traffic streams be separated by a barrier, as drivers could be required to drive on the opposite side of the carriageway to that normal on public roads. A barrier may extend beyond the ends of a ramp or crossover to discourage drivers from attempting to drive in the wrong lane.

Fig. 4.16 illustrates the use of a helical ramp. Usually, helical ramps are external but may be internal. The recommended direction of flow in the UK is clockwise, that is with the driver on the inside of the turn. This is recommended for ramps of minimum radius. With a larger radius, an anticlockwise flow is acceptable: ramps are in use with an anticlockwise flow.

Concentric helical up-and-down ramps, serving alternate floors, may be used in larger car parks. In such instances, the outer ramp should be the up-ramp as it will have the lesser gradient.

4.4.7 Choice of layout

The factors affecting car park layout are so many and variable that it is impractical to propose ideal layouts. The predominant use to which the car park will be put should be borne in mind. A primary consideration is the duration of stay, which varies with the trip purpose. Parking may be less than one hour for shopping, but for business trips the duration is usually longer; it is even longer for work trips. For park-and-ride (e.g. at a railway station or airport for short-haul travel), the facility to park without delay is important.

The search path of 500 bays is the ideal maximum. Therefore, car parks of more than 500 bays should ideally have more than one search path. Car parks with internal ramp systems have been built of substantially greater capacity than 500 bays but, as previously mentioned, public car parks are commonly used at well below their design capacities. If an attempt is made to use such a car park near its capacity, delays can be expected. A short search path will provide incentive to short-duration parking or to park-and-ride travellers.

In larger car parks, long circulation aisles are inevitable. This can lead to excessive vehicle speeds if no controls are provided. Typically, speed humps are suggested as a form of speed control. However, these must be considered in the context of fixings and waterproofing maintenance, slab loadings, and headroom restrictions.

For larger car parks, the preferred layout is usually the flat deck with straight or helical clearway ramps (sees Fig. 4.11).

Internal variable message signs can be used to manage circulation and to divert drivers past full floors or areas. These must be carefully designed with good visibility of signs located before the decision point. The system also requires good levels of management and maintenance.

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5.1 Loading

5.1.1 Design loads

The imposed loading applicable to decks and ramps in car parks is given in standard codes e.g. BS 6399: Part 1[5.1]in the UK. Vehicular weight has tended to diminish with time, but the payload has increased. Consequently, the design load has remained constant in successive loading standards.

5.1.2 Uniformly distributed imposed loads

For a normal mix of vehicles, subject to the maximum weight of any vehicle being 2500kg, the imposed uniformly distributed load given in BS 6399: Part 1[5.1] is 2.5kN/m^2. There are local loading variations, which should be verified even when designs are referenced to UK codes; for example, in Hong Kong a uniform distributed imposed load of 4kN/m^2 is adopted. Consideration should be given to modifying this figure if the weight of vehicles entering the car park exceeds 2500kg, or if vehicles are to be packed more densely than normal by automated systems. For multiple floor loads it is recommended that the approach in BS 6399: Part 1[5.1] be adopted. For car parks, this does not allow any reduction in column load from loaded areas and requires that all storeys be assumed to be simultaneously loaded.

Snow loading on roofs need not normally be considered in combination with vehicle loading, unless the car park is being designed for long-term parking, or in an area with high snowfall.

5.1.3 Wind loads

The wind speeds and loading applicable to car parks are determined from standard codes[5.2] and advice notes[5.3]. Sufficient voids must be provided in cladding to ensure adequate ventilation. Percolation through the building will result in drag on the bodies of the parked vehicles and will be transferred to the floors by shear in the tyres. It is therefore recommended that the wind loading be taken as acting over the entire elevation area of the structure with no reduction for openings.

Local wind pressures on cladding components must be designed on the basis of maximum pressure and suction being applied to both faces of each cladding component simultaneously.

5.1.4 Other lateral loads

In addition to wind load, car park structures should be designed to withstand vehicle impact loads. Lateral loads also arise from vehicles changing direction vertically at ramps, and from friction when they turn or brake. Horizontal loading is more important in car parks than in other building types where additional stiffening is derived from partitions and finishes.

Lateral loads should be safely transferred to the foundation through the structural system, e.g. slabs, beams, bracing and columns.

5.1.5 Ground pressures

Lateral soil pressures on the walls, uplift and ground heave pressures under the ground-bearing slab, and flotation will dominate the design and construction of basement and semi-basement parking levels. The scale of such pressures is likely to be several orders of magnitude higher than the normal imposed dead or live loads on the floor slab. The most critical flotation case is often during the early stages of construction. Provisions for drainage of the basement and ground in the immediate vicinity must be considered. Further advice is available in *Design and construction of deep basements*[5.4].

5.1.6 Load combinations for normal design situations

Loading on car parks is generally similar to that on other buildings. However, the ease with which imposed load can be moved makes the analysis of pattern loading cases important. Thermal strains induce forces that, if restrained, can be significant, particularly for exposed roof slabs.

Structural design should be carried out with critical combinations of dead load, imposed live load, wind load, thermal load, the notional live loads from relevant parts of BS 6399: Part 1[5.1] and the other lateral loads as listed in Sections 5.1.4 and 5.1.5. Design against flexure, shear and torsion should be carried out, using design methods and partial safety factors according to the appropriate codes of practice for the structural material and construction type.

5.1.7 Load combinations for abnormal design situations

The following loads should be considered using a partial factor for loading of 1.05. Where access to the car park for emergency vehicles such as fire engines is required, the design loading may have to be increased.

(i) *Punching shear of jack or wheel loads on slabs less than 150mm thick*

Floor slabs should be designed to carry the more onerous of the following:

(a) wheel loads shown in Table 5.1. The figures are based on the maximum tyre pressures recommended for given tyre sizes.
(b) a jack load of 12.5kN acting over 50 × 50mm. This contact area need not be considered closer than 0.75m to a floor edge.

Table 5.1: Wheel loads

Contact area (mm)	Imposed load on flat slab (kN)
150 × 150	6.5
175 × 175	9.9
≥ 200 × 200	12.5

If traffic-calming measures such as ‘sleeping policemen’ are used, it must be demonstrated that the equivalent static loading remains below these values. It is generally preferable to use post or barrier control features to avoid impact loads on slabs and maintain headroom.

(ii) *Vehicle impact into a column*

Vehicle impact may be from within, either directly or by transmission from the edge protection barriers, as explained in Section 5.6. Impact may also be from outside the car park at ground level.

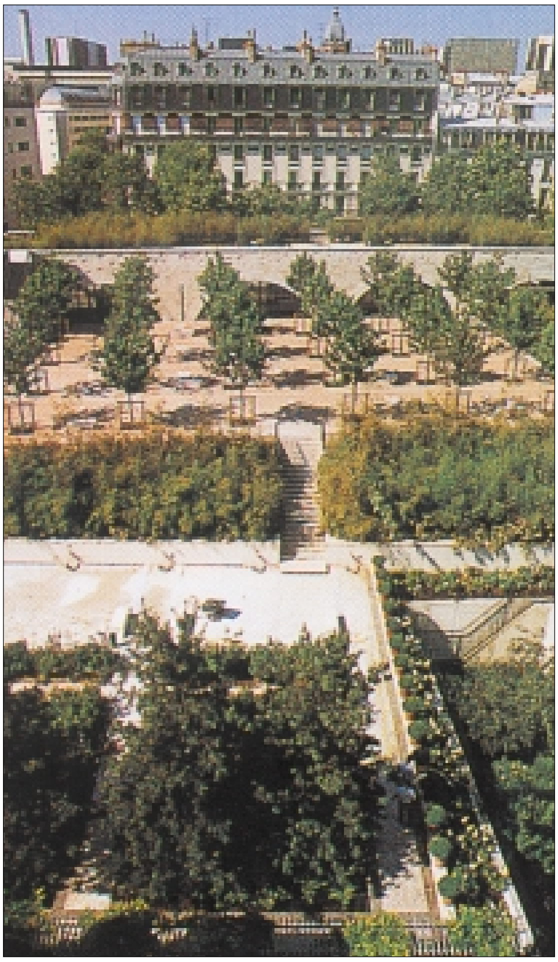


Fig 5.1 Parc Hector Malot underground car park, Paris, showing a selection of landscaping features

5.1.8 Robustness of structural frame

Car-park structures should have provisions for robustness as given in the relevant codes of practice.

In the UK, *Building Regulations Approved Document Part A*[5.5,5.6] and the codes of practice for construction materials should be referred to for measures against collapse disproportionate to the cause, e.g. a local accident, effects of fire, etc.

5.1.9 Landscape loading

A wide variety of loading may result from different landscaping schemes for roofing areas and must be carefully considered. In deriving the appropriate loading, account must be taken of the particular planting scheme required, mature size of plants, and flexibility for future changes. The imposed loading from landscaped areas, water features and concentrated tree loads can be an order of magnitude higher than the normal vehicular imposed loading for car parks. Even where thin, drained grassed areas are proposed, it is recommended that a minimum imposed load of 7.5kN/m^2 be adopted. Similarly, loads from water features and rock features must be carefully considered as they can add significant loading, limit flexibility for future changes, increase structural costs and require a continuing operation and maintenance commitment.

In deriving the loading to be applied, the long-term growth and access requirements for maintenance plant, which can impose concentrated loads, must be considered. The provision of tree planters (see Fig. 5.1) in particular must be carefully planned, as the increased depth of soil required (typically at least 1.5m), weight of the mature tree, and overturning effects of wind loads all lead to concentrated and local loading. In the absence of more specific details, it is recommended that a percolation factor of 50% be used in conjunction with the projected elevation of the fully mature tree to derive wind forces. Use of overturning loops below or at the soil surface should be considered to anchor trees adequately. In general, the cost of supporting trees is high and, for economy, they are normally placed over column and/or principal support positions.

The features of landscaped areas will normally include provision for drainage, irrigation and access for maintenance. Owing to the difficulties of access to inspect membranes and the need to both irrigate and drain landscaped areas, such areas will normally require an enhanced waterproofing membrane and a root barrier or positive measures to prevent structural damage by root penetration. The membrane must be adequately protected to prevent damage from horticultural maintenance. The soil must be properly drained, without being too steep, and falls of 1:100 to 1:40 would normally be used in conjunction with a positive drainage system to ensure the soil does not become saturated (see Fig. 5.2). Loading must consider the effects of blockages to the drainage system and the increased loads resulting from storm inundation.

The roof loading must allow for the maximum weight of vehicles that will be used for maintenance, such as tractors and grass cutters, which can impose concentrated wheel and patch loading. Provision of edge barriers, means of access and means of avoiding steep slopes requiring frequent maintenance must be properly dealt with so that landscaped areas can be safely maintained.

Water features are often considered to be a desirable component of a landscaping scheme. They also impose loading significantly higher than normal car-park loading and, as with landscaping in general, must be carefully considered for each project.

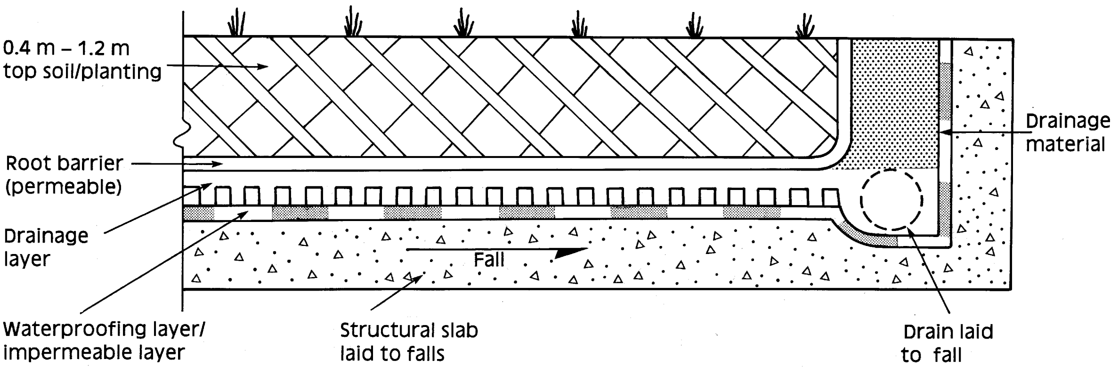


Fig 5.2 Minimal roof planting details

Fig 5.3 Buttercrane car park, Newry, Co Down – cellular beams with PCC units

The restrictions of loading, the requirements to control growth, and the maintenance regime to ensure loading does not exceed the design level must be clearly defined and agreed with the project client as part of the brief. This information is an essential part of the operational manual and health and safety file.

5.1.10 Response of structure to vibration

Empty car-park structures lack the damping normally provided in buildings by partitions and finishings. However, the dynamics of most car park structures are generally found to be satisfactory when the design complies with normal Section sizes that give natural frequencies above 5Hz. Spans of 16.5m can have natural frequencies in the range 2–4Hz, which will require special consideration of user comfort. Unusual or long-span structures may be more sensitive to dynamic loading and their responses should be checked. In service, dynamic response usually becomes less of a problem as parked vehicles increase the mass.

5.2 Structural materials

5.2.1 Materials

Conventional materials commonly used in car-park construction are concrete and steel, combined in a variety of ways. Concrete may be both reinforced and prestressed. Steel is used either alone as the principal structural material, or compositely with concrete.

5.2.2 Concrete construction

Concrete car parks may be assembled from precast units or cast *in situ*. *In situ* concrete structures may be cast on a wide variety of proprietary formwork and falsework systems; proprietary lift-slab methods avoid the need for formwork for some types of car park.

The use of lightweight-aggregate concrete can also be considered. In car parks, the weight of the concrete slab usually exceeds the live load, and a 25% reduction of this weight is significant, both in the slab and in its effect on column and foundation loads. Lightweight concrete also offers better fire performance. This must be set against the disadvantages: a smaller permitted span/depth ratio, additional shear reinforcement in the slab, and in composite beams a slightly reduced effective breadth of flange and an increased number of shear connectors.

5.2.3 Steel construction

Uncased structural steelwork is often used in car-park structures. Its use in above-ground car parks received considerable encouragement from the results of research into the potential fire hazard represented by a loaded car park. These tests suggested that existing requirements for fire resistance could be relaxed in certain circumstances that, in practice, apply to most multi-storey car parks. However, in some cases it may be necessary to apply for a relaxation of the regulations from the appropriate authority. If in doubt as to whether an application is required, the position should be checked with the appropriate authority. Maintenance costs are likely to be higher for uncased steelwork than for concrete, but the difference is not considered to be great.

5.2.4 Composite construction

Car parks in composite construction generally comprise a framework of steel beams and columns supporting concrete floor slabs (see Fig. 5.3). The latter usually combine in composite structural action with the steel beams in one or both directions and can be wholly cast *in situ* or precast with *in situ* joints and topping. Some of the advantage in speed of erection afforded by prefabrication may be lost if wholly *in situ* construction is adopted for floor slabs.

5.3 Methods of construction and structural design for car parks above ground

The structural form of a multi-storey car park will be heavily influenced by the design geometry adopted – see Chapter 4. Designs commonly use *in situ* concrete, precast concrete, structural steel, or a combination of some or all of these materials. Guidance on the location of columns is given in Section 4.3.4.

5.3.1 Floors

With the exception of some temporary structures, car parks use concrete for the deck structure. It is recommended that all be laid to a minimum 1:60 fall. This requirement can complicate deck joint details, and must be borne in mind from the outset.

The car-park decks must also be designed to resist the horizontal and vertical loads applied by cantilevered edge-protection systems and fixing arrangements.

Roof decks usually have a waterproofing layer. However, to limit cracking, some deck construction methods can conform to water-retaining design standards. Waterproofing can then be omitted if there is adequate resistance to frost. Water-retaining specifications do not guarantee that there will be no opportunity for water penetration, but will generally reduce crack widths. As with any system, care still has to be taken at joints.

It is important to realise that high chloride concentrations can occur on car park decks, owing to vehicle-borne salt combined with poor drainage and detailing. This could cause reinforcement corrosion, particularly in top steel for slabs continuous over supports and especially for roof slabs. Refer to Chapter 8 for more information on durability issues.

The main types of floor construction are:

Precast concrete hollow-core slabs. Units (see Fig. 5.4) are factory mass-produced pre-tensioned voided units, produced by long-line methods and sawn to length. They use high-strength concrete, typically 60N/mm^2, and have high standards of quality control. However, they are only reinforced longitudinally: for this reason, combined with the need to achieve a suitable running surface for vehicles, it is

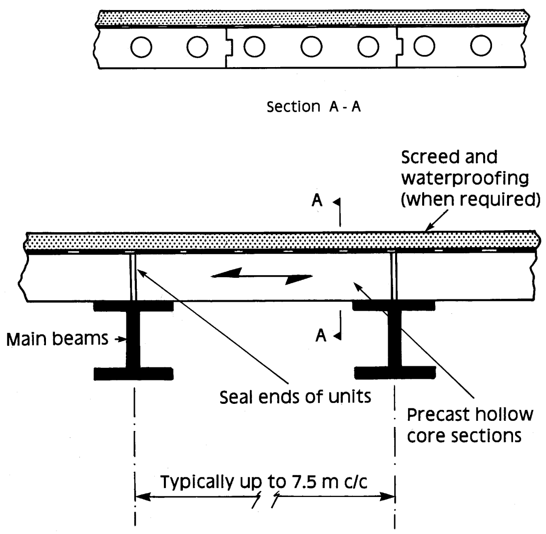


Fig 5.4 Typical hollowcore slab detail

usual to use them compositely with an *in situ* structural concrete topping. Units can easily accommodate clear spans of 15.5m under normal vehicle loading, although shorter, shallower spans are more common. It is important to ensure that drain holes or other provision be made for trapped water to escape. It is also necessary to protect exposed reinforcing strands at the unit ends.

Precast concrete permanent shuttering. Units (see Fig. 5.5) are typically solid and 50mm or 75mm thick, and may be reinforced or pre-tensioned. They are usually cast individually. Units are designed to span between primary beams and to act with an *in situ* structural concrete topping. Precast units may require propping during construction and a practical span of up to 4.8m is achievable, limiting applications of this method.

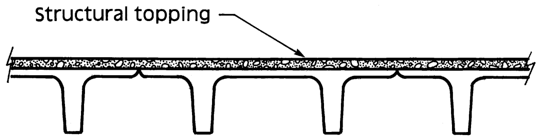


Fig 5.6 Precast concrete double tees slab section

Precast solid slab. This form of construction has limited span capacity, but forms an economic solution when used compositely with steel beams. The method is used in proprietary systems to provide some of the thinnest decks.

Precast concrete double tees. Units (see Fig. 5.6) are cast using a long line pre-tensioned method, but individually shuttered with stop ends to form the unit ends. They are typically 600mm deep for 15.5m clear span. They may be used with an *in situ* structural concrete topping, in which case a top flange depth of 75mm is common, or without *in situ* topping, in which case the top flange thickness is likely to be at least 100mm. The long-line process means that it is necessary to provide *in situ* protection to the exposed reinforcing strands at the unit ends. If constructed with no *in situ* structural topping, great care has to be taken to accommodate pre-cambering and waterproofing.

In situ flat slab. Flat-slab construction is often proposed for car parks, since it can reduce clear floor heights. The slabs can be reinforced or post-tensioned and with uniform thickness or waffle construction. Two-way spanning *in situ* flat-slab construction can economically fit column spacings up to 8m. There are proprietary systems in which slabs are stack cast at ground level and jacked into position. Careful detailing and construction are required at the slab–column interface to

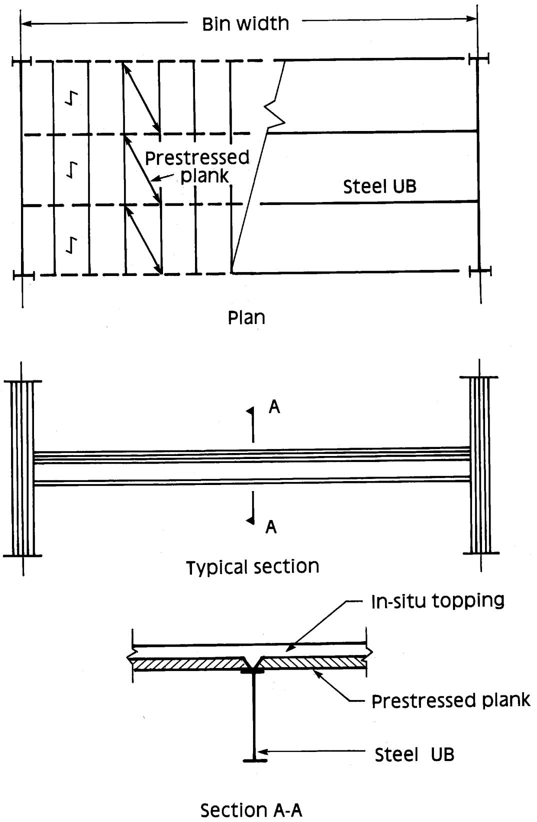


Fig 5.5 Precast concrete permanent shuttering

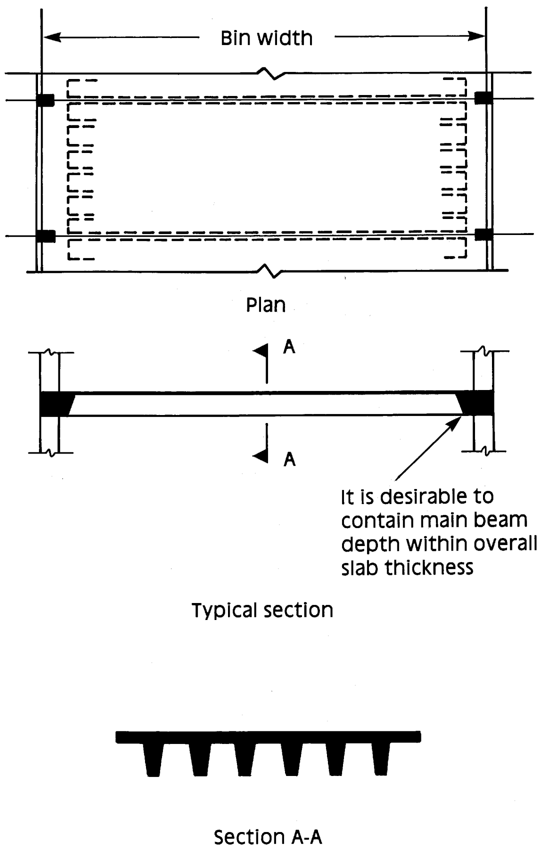


Fig 5.7 *In situ* concrete ribbed slab

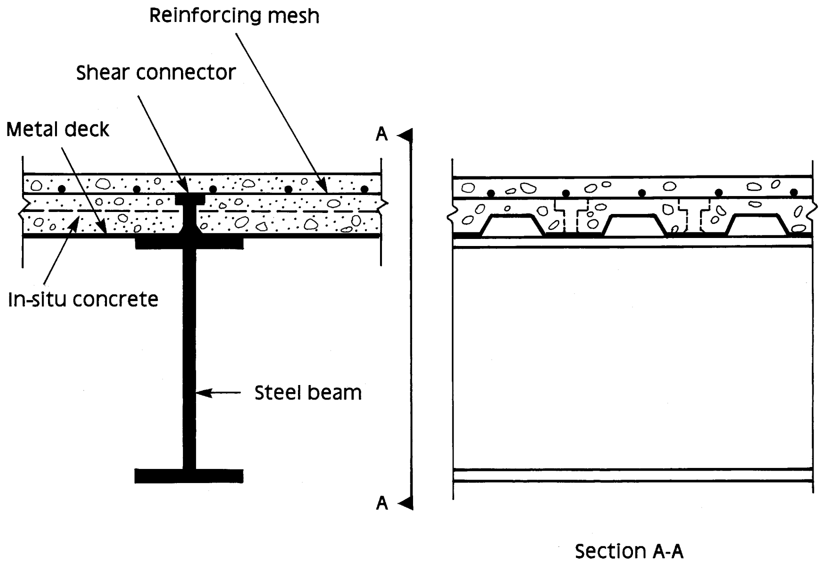


Fig 5.8 Metal decking permanent shuttering

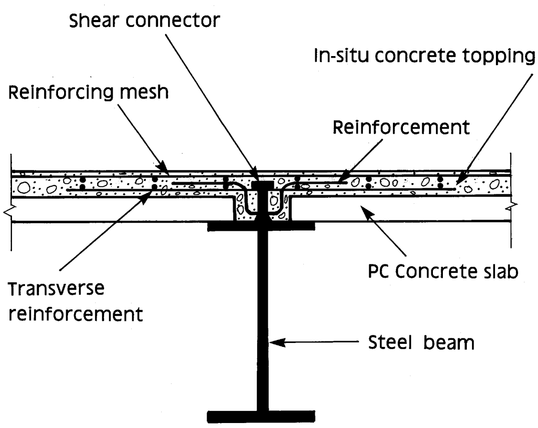


Fig 5.9 Composite beam, slab and structural topping

Fig 5.10 Clear span frame arrangement

prevent cracking and/or moisture paths that can promote corrosion of critical joints (see Chapter 8).

In situ concrete ribbed slab. Ribbed concrete slabs spanning one way (see Fig. 5.7) can easily be configured to deal with both long- and short-span solutions. Usually they are of reinforced construction, but post-tensioned solutions are also possible. It is important that continuous designs pay proper attention to the possibility of chloride ingress, as main slab reinforcement will be at the top of the slab at the supports.

Metal decking permanent shuttering. Galvanised steel metal decking (see Fig. 5.8) can be used as permanent shuttering and can be designed to act compositely with an *in situ* structural concrete topping. Measures must be taken to prevent water ingress through the concrete topping, both during and after construction. Trapped moisture and condensation can cause hidden corrosion of the metal decking and will require specialised perforated units. Exposed roof slabs are particularly susceptible to such effects. Sealing the top surface may aggravate this condition and an enhanced maintenance regime will be necessary. For these reasons, this system is rarely used for car-park structures.

Structural concrete toppings. Thin *in situ* concrete toppings (see Fig. 5.9) are commonly used in conjunction with either precast concrete units or permanent steel or concrete shuttering. Welded mesh reinforcement mats are frequently used. It is important that details are developed that take into account such issues as:

- reinforcement details at sheet overlaps to maintain specified cover
- pour sizes and shrinkage
- concrete grade and mix design (see Chapter 8)
- influence of camber and/or deflection on structural topping thickness
- workmanship during construction, in particular compaction and support of reinforcement to prevent displacement during pouring and finishing operations.

Toppings thinner than 75mm are difficult to construct.

Steel decking. Steel decking may be suitable for car-park floors, and has certainly been used for temporary car parks. Care should be taken to provide adequate skid resistance, and there are issues concerning durability. Steel decks tend to be thin and can be sensitive to vibration. They also tend to transmit noise.

5.3.2 Frames

The design solution for the floor slab and the constraints on the column positions (see Chapter 4) will largely dictate the form and type of principal framing adopted (see Figs. 5.10, 5.11 & 5.12). Each of the main types of floor construction usually has a compatible framing system, being either:

- precast
- *in situ*
- structural steel.

Integral framing solutions
The framing system for the in situ concrete flooring options is designed as an integral part of the floor slab. This is also true for steel frames incorporating composite beams of steel girders and concrete slabs.

Fig 5.11 Singly propped frame arrangement

Fig 5.12 Cantilever frame arrangement

Separate framing solutions
Separate frames are typically used in conjunction with precast floor construction. The precast floor slabs are characterised by long-span decks with the support frame span – either steel or precast – minimised to accommodate the large end reactions. A span of three bins is typical. The primary beam can either be part of the precast system or *in situ* concrete. Cranked precast floor units can be effective in reducing secondary framing at ramps. With arrangements using long spans or split-level floors in combination with short columns, particular care is required to prevent local cracking on the column.

5.3.3 Foundations

The design of foundations should follow normal practice[5.7]. Guidance on this may be obtained from *Allowable settlements of buildings*[5.8] and *Soil-structure interaction – the real behaviour of structures*[5.9]. Care must be taken when considering articulation of any potentially stiff continuous members to avoid cracking of concrete or unacceptable structural distortion in steel. It should be borne in mind that loadbearing ground-floor columns and walls may not be restrained by the ground-floor structure and may be subject to vehicle impact from without and within. Foundations must be designed to have sufficient lateral resistance to these loads.

The lighter weight of a steel-framed structure compared with a concrete frame can have a significant effect on foundation costs in certain soil conditions[5.10, 5.11]. The reduced weight coupled with the structural flexibility provided by this form of construction can permit column loads to be carried by pad foundations. A heavier rigid building on the same site may require some form of ground improvement at pad locations or a different foundation solution such as piles or a rigid raft.

5.3.4 Ground floors

Several options are available for ground-floor construction. The choice of a particular type will depend on ground-bearing capacity, relative levels and client preference. They can be summarised as follows:

Asphalt. A flexible asphalt construction will usually be economic where low ground-water level and reasonable ground-bearing capacity exist and where the client has no objection to a dark coloured finish. In general, asphalt finishes must be laid after completion of the superstructure – limited headroom may exclude mechanised laying techniques.

Brick or concrete paving. Brick or concrete paving offer an alternative to asphalt. Hand-laying methods suit the restricted headroom well, and a light coloured surface is easy to achieve.

Concrete. An *in situ* concrete slab either ground-bearing or suspended is suitable for at-grade slabs where ground conditions are poor or where water levels are high. *In situ* concrete also offers good durability and the light coloured finish is often favoured by clients. *In situ* concrete is also suitable for basements and semi-basements and where high ground water levels are possible. In these circumstances, issues such as flotation, waterproofing, joints and service penetrations should be carefully considered (see Section 5.4).

5.3.5 Lateral stability

All the common ways of providing lateral stability by use of lift or service shafts, shear walls and cross bracing can be employed in car-park structures. Positioning of the lateral stability systems must take into account maintaining circulation, sight lines and a light aspect as well as discontinuities at movement joints. The location of the lateral load-resisting system within the structure is particularly important to control stresses when high thermal loads are predicted.

5.4 Methods of construction and structural design of underground car parks[5.2, 5.9, 5.10]

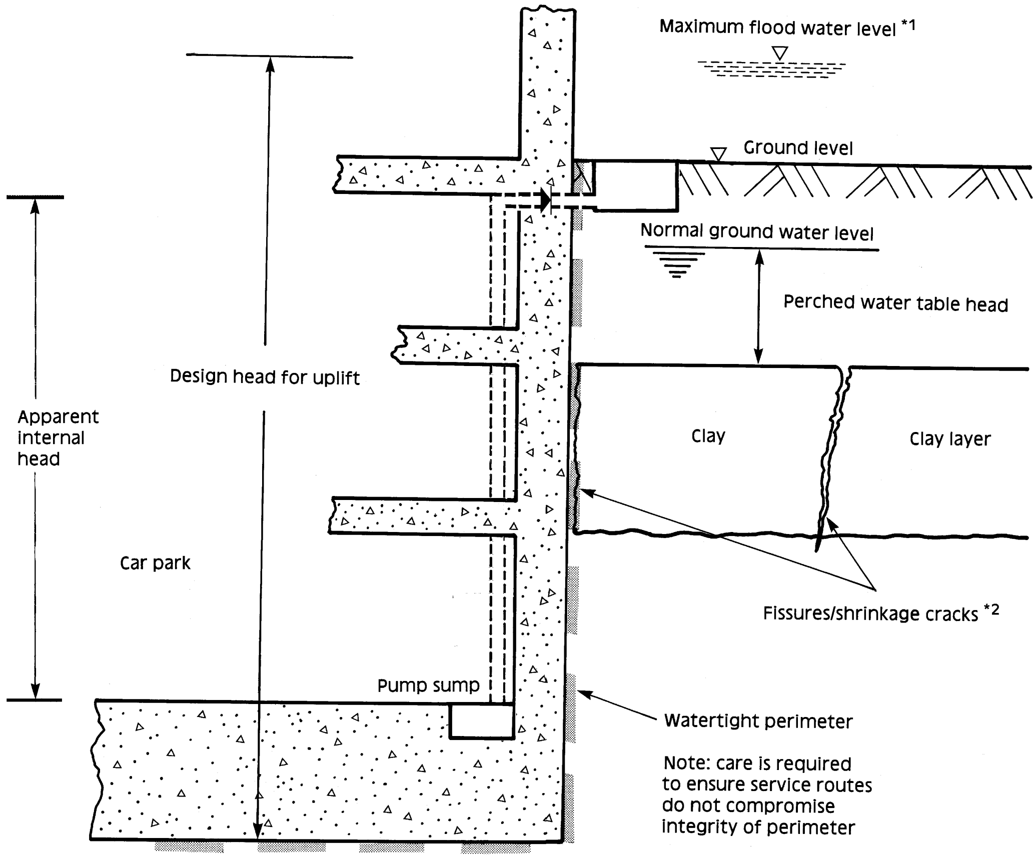
The available site area, proximity of adjacent structures, flotation issues and methods of construction are the principal design constraints in generating the geometry and structure of underground car parks.

5.4.1 Categories of underground car park

There are two main categories of underground car park:

(a) Car parks below buildings where the shape of the car park is usually controlled in varying degrees by the shape of the building above; column positions are dictated by

Fig 5.13 Hydraulic linkage and design head considerations



Notes

*1 The alignment for approach ramps and flood protection measures may mean flood water levels can exceed adjacent ground levels without flooding the car park entrance ramps.

*2 The presence of even small fissures in the clay or less pervious soil will allow the full pressure head to develop, even if flow rates are low.

integrating the design of the car park with the building above and column sizes are likely to be large. The use of transfer structures, where the geometry of the grid is changed, is usually expensive and not adopted without good reason.

(b) Car parks below open spaces such as roads, squares, sports areas, public parks or similar public access areas. Their geometry is controlled by the method of construction access or by the geometry of circulation. The use of the area above the car park for landscaping, highway or public access, or even canals, will affect the structural form of the car park. Provisions for tree boxes will require greater storey heights.

5.4.2 Methods of construction

The methods of construction are identical to those for constructing deep basements; selection of the method depends critically on soil and groundwater conditions. Where a basement is to be constructed up to the boundary of the site, the space required for the temporary and permanent works may be a prime consideration in the method selected. Sometimes, these methods are directed at avoiding temporary works by using the permanent structure of the finished building to provide temporary support as excavation proceeds. Such methods are generally only used when traditional temporary support methods are precluded by cost or space considerations.

The following methods minimise temporary works and are often used for top-down construction:

- Diaphragm walls
- Contiguous pile walls
- Sheet pile walls.

Where space permits and the geotechnical conditions are appropriate, open cut excavations can provide an economical solution.

5.4.3 Control of ground water

As car parks are lighter than other building structures, specific consideration must be given to the method of controlling and managing water ingress and the potential development of uplift pressures. Loads arising from even modest depths of water will give rise to significant effects – particularly in the temporary construction state before full dead loads are imposed – and may give rise to instability if not properly addressed. An uplift pressure of 10kN/m^2 per metre of unbalanced water depth that can arise above the base level must be considered in both the permanent and temporary load cases. In clay soils, the pressure linkage through drainage and fissures, in flood conditions, and the possibility of perched water tables must also be considered.

This can give lead to additional uplift pressures.

Using pumped systems or pressure-relief valves to limit uplift pressures often appears to provide initial economy, but will require a constant operational and maintenance commitment throughout the life of the structure to ensure significant uplift pressures cannot be generated. The operational cost, risk and consequences of failure of such systems must be balanced against the initial costs of fail-safe provisions through the use of thicker base slabs or tension piles in conjunction with watertight boundaries to overcome potential buoyancy. Acceptance of the consequences of the risks of pumping and other alternatives – such as provision of pressure-relief valves to allow controlled flooding of lower levels and balancing of water levels in extreme circumstances – may be considered acceptable for some car parks but must be agreed in advance with the client and relevant authorities.

Even with watertight boundaries, it is recommended that underground car-park levels be equipped with positive drainage systems linked to pumps and sumps to allow surface run-off and wash-down water to be removed. Great care must be taken in detailing service provisions to ensure the watertight perimeter is not compromised by service connections and ducts that could lead to water ingress (see Fig. 5.13). It is particularly important to agree the acceptance criteria and required environment for basement and underground car parks with the client, e.g. the level of humidity or condensation that will be acceptable. This is essential before structural and ventilation design works and can be an area of significant misunderstandings if issues are not clearly addressed and agreed.

5.5 Designing for movement

Structural elements of car parks are susceptible to movement both during and after construction. Some of the principal reasons are:

- elastic structural deflections
- temperature changes during construction and in service
- shrinkage
- creep
- differential settlements.

With careful design, appropriate joints can be provided to accommodate such movement and to suit the structural design. Car parks can suffer from premature deterioration if the sealants break down – e.g. under traffic loading – allowing water and salts to get into the joints (see Chapter 8).

Allowance should be made for the fact that the exposed nature of car park structures produces a greater design temperature range than in other building structures (see Appendix A). Joints must also take account of the potential for differential movements between the relatively flexible car park deck and the stiff zones created by ramps and access shafts. Typical mastic joint fillers can accommodate around 20% strain, so a mastic-filled joint would typically need to be five times as wide as the predicted movement. Elastomeric joint fillers are generally regarded as more effective for joints with large predicted movements. Their additional cost must be balanced against potentially expensive remedial work in the event of joint sealant failure.

Concrete Society Reports TR 22 *Non-structural cracks in concrete*[5.12] and TR 44 *The relevance of cracking in concrete to corrosion of reinforcement*[5.13] provide valuable guidance on various causes of cracking, which can lead to premature deterioration of structural elements. Structural design should also be aimed at controlling such cracking, mainly resulting from differential strains due, for example, to restrained movements at the interface between pours or between precast and *in situ* concrete.

5.5.1 Deflection

The prediction of long-term service deflections is of great value to confirm that falls are and will remain sufficient to prevent the ponding of water on surfaces or in concrete drainage channels.

In normal circumstances, falls of 1:60 are considered adequate to accommodate the effects of deflection under load and pre-camber, and construction tolerances. For less usual conditions, such as long-span beams or transfer structures, detailed calculations of deflection should be undertaken to ascertain that the slab drainage strategy is not compromised.

5.5.2 Temperature

Multi-storey car parks are different from other buildings, in that they have a structural frame that is usually fully exposed to the external air. This means that the effects of temperature-induced movement[5.14] must be specifically considered and catered for. These structures can be considered as intermediate between bridges (where temperature loads are well codified and established), and normal building frames where the structural frame is normally within a controlled environment.

Temperature movements are restrained by the lateral stability systems. Careful consideration should be given to the location and interaction of such systems to avoid the large forces being generated by restrained thermal movement. In concrete structures, these can lead to load reversal, causing cracking of elements not designed to resist the stresses induced. Constrained expansion often occurs inadvertently between the deck and ramps or stair structures. If the adverse interaction between lateral restraint systems cannot be avoided, then either the system should be isolated from the slab, or a movement joint should be introduced to separate the systems. Care must be taken to provide for any lateral load transfer function to be maintained.

Temperature differential through top decks will cause thermal bowing in summer. This requires consideration when deck joints are being configured (see Appendix A).

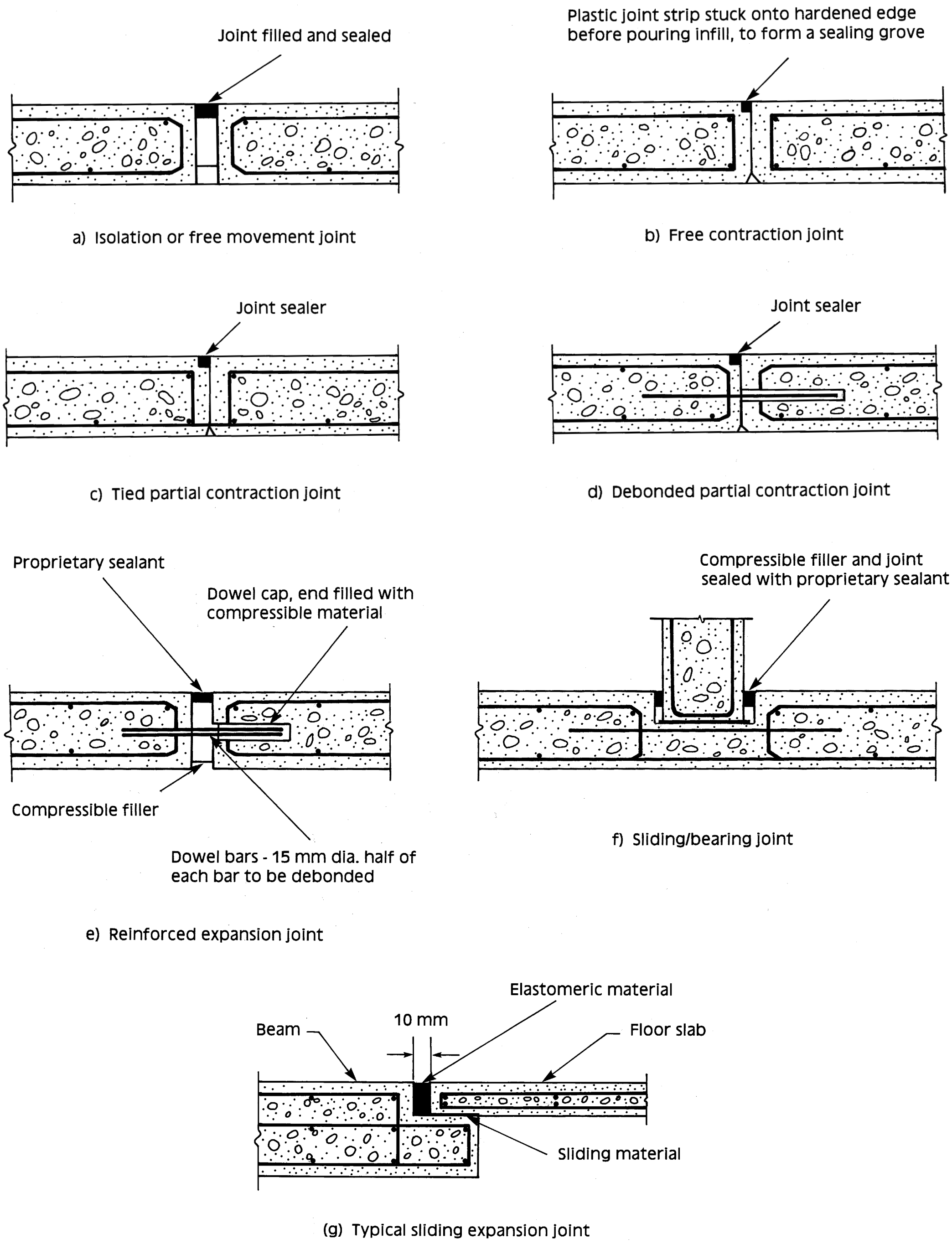
5.5.3 Shrinkage

Shrinkage in concrete should be accounted for in the design of the deck, for example as given in BS 8110: Part 2: 1985[5.15]. It should be noted that the characteristics of shrink and creep vary in different countries and climates. For example, tropical or equatorial zones with high temperature and humidity, such as Hong Kong, will differ significantly from the basis stated in BS 8110.

In general, precast concrete deck and frame elements will have largely completed their shrinkage cycles by the time they are incorporated into the structure. However, shrinkage must be considered in the configuration and sequencing of *in situ* concrete frames and decks, or any system with a continuous *in situ* concrete topping. Post-tensioning, if used, will cause elastic shortening, the effect of which must be taken into account.

Frame shrinkage must be considered and accommodated by joints in brittle facing materials such as brickwork. Joints in façades are normally required at much closer centres than those in the principal structure. For example, brickwork may require joints at 9m–12m centres and horizontal supports may also be required to restrain brickwork panels.

Fig 5.14 Examples of movement joints



5.5.4 Creep

Creep can have a significant effect on the deflection of reinforced or prestressed concrete units over time. Methods for calculating its effects are well documented in Part 2 of BS 8110[5.15]. Creep can be more significant for concrete car-park construction than other structures for the following reasons:

Prestressed solutions. There is usually pressure to minimise column frequency to improve vehicle circulation. This often leads to prestressed floor designs.

Load ratio. The ratio of dead load to total load tends to be higher in car parks than in other structures. A typical concrete car park when completed (but empty) can be 75% loaded. This compares with approximately 50% for typical office structures. A high proportion of the design imposed load is also achieved in service.

Creep significantly modifies the effective elastic modulus of concrete beam members over time. This can mean that members whose deflection performance is adequate shortly after construction can be inadequate after perhaps 10–20 years. Deflection of concrete beams can increase by approximately 25–50% which can adversely affect drainage provisions.

It is essential that adequate consideration be given to the creep effects and their effect on the drainage strategy at the design stage. It is usual to locate gully outlets and downpipes at column positions. Creep and consequential long-term deflection of concrete beam members can lead to ponding at beam mid-span or cantilever tip locations.

5.5.5 Movement joints

Adequate allowance must be made for car-park structures to respond to temperature-induced volumetric change, and for shrinkage of reinforced or prestressed concrete structures (see Fig. 5.14). See also Sections 5.5.2 and 5.5.3.

An example of calculations for assessing temperature effects and a procedure for assessing them are given in Appendix A.

Table A.1 shows that a typical design temperature range (taken from BS 5400[5.16]) for a car-park top deck in the UK can be 45°C. On this basis, for a 60m-long structural frame, the movement joint may have to deal with thermal movements of the order of 30mm. The movement joint must be able to accommodate this movement in addition to shrinkage and creep[5.17].

Installation of movement joints must also take account of the season of construction. Ideally, joint widths should be adjusted during construction to suit the temperature conditions prevailing at the time of installation and seek to minimise the range of post-construction movement. As with all joints, provision should be made for easy replacement of components with a design life less that the main structure (see also Chapter 8).

5.6 Edge protection

The edge protection for car parks must fulfil two primary safety functions:

- vehicle crash/restraint barrier
- pedestrian/child safety barrier.

The dimensions of barriers must comply with national standards such as BS 6180: Part 1[5.18]. In its capacity as a vehicle crash barrier, the edge protection must keep an errant vehicle within the structure. Car parks are usually constructed in city centres with extensive pedestrian access around the outside of the structure. The requirements for containing the errant vehicle include the constraint that any impact does not dislodge the cladding onto pedestrians.

For structural design, it is essential to limit the energy imparted by an errant vehicle to a barrier or column and accept such an incident as a local accident. The design should be aimed at avoiding any large-scale damage and disproportionate collapse of the structure. (See *Approved Document Part A*[5.5, 5.6] and Eurocode ENV1991-2-7[5.19].)

The cost of edge protection represents a significant component in the cost of a car park and warrants careful consideration. Proprietary car park systems may rely for their economy on the interaction of barriers with the frame.

5.6.1 Designing edge protection

There are three principle types of crash barrier: those that span between primary structural members (commonly horizontally between the columns – see Fig. 5.15), those that cantilever up from the car park deck (see Fig. 5.16), and those that are monolithic with the deck (see Fig. 5.17).

Fig 5.15 Circular hollow section vehicle restraints spanning horizontally between columns

Fig 5.16 A restraint post cantilevered from the car deck (after impact on rail)

Fig 5.17 A monolithic concrete upstand restraint (after impact on rail)

The first type consists mostly of hot-rolled steel sections that absorb the vehicle energy by yield mechanisms. Recently, wire systems have also been proposed. Fibre composite systems that absorb energy by fracture mechanisms are also potentially suitable.

The second type consists of cold-formed section rails supported on either cold-formed posts or hot-rolled steel posts. The most common rail is the standard section motorway barrier, with trapezoidal-section and sigma-section open-box beams also used. The posts can be subdivided into two further categories: stiff, fully welded construction of post with its base; and flexible posts incorporating spring steel construction, or an energy-absorbing buffer between the post and its base.

The third type is of monolithic concrete construction with continuity reinforcement between the wall and floor deck. Most of the load is carried by cantilever action, though in some cases the barrier acts as a three-sided supported slab. The relative rigidity and greater mass of such a barrier means that it relies on the momentum at impact being distributed throughout much of the structure and on energy being absorbed by elastic strain.

5.6.2 Expected performance

Vehicle crash barriers are required to withstand a notional load representing vehicle impact. They should not deflect excessively, fail catastrophically or permit the vehicles to ride over the top. In the UK, barriers are designed to BS 6399: Part 1[5.1]. As a part of the inspection and maintenance, testing may be required to assess barrier effectiveness – for example, if there is a reason to believe that a barrier may have inadequate strength owing to deterioration or after an incident involving excessive accidental impact. Testing may be particularly relevant to older car parks, which may not have been built to current design rules. Details of such tests are given in the document *Edge protection in multi-storey car parks – design specification and compliance testing*[5.20].

The barrier must not deflect by more than the clear distance between the original position and any cladding made from a brittle material. The total deflection of barriers spanning horizontally should not exceed 600mm. Where barriers provide pedestrian restraint, they must not deflect beyond the edge of the deck, except at split levels. Deformation of the barrier beyond repair (i.e. requiring replacement) is acceptable providing it does not lead to progressive collapse. It must be replaced if damaged.

5.6.3 Fixing protective barriers

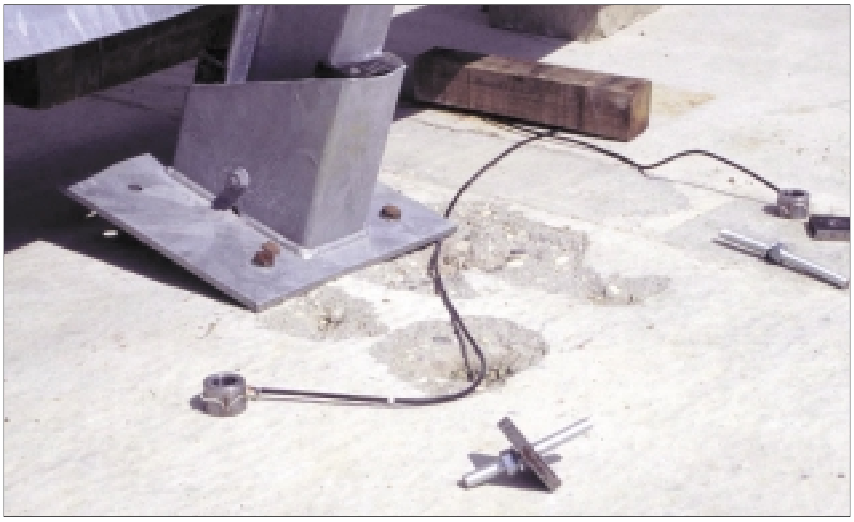
Any fixing bolts on which the barrier support relies for attachment to the structure must not fail or pull out (see Fig. 5.18). However, as long as the barrier beam is contained in a fail-safe configuration (such as between column flanges), locating bolts may beneficially be designed to fail to restrict damage to the primary structural members (e.g. columns).

Cantilevered barriers attached directly to the concrete deck should have fixings that are rigidly anchored into the concrete. Through-bolts with plate washers beneath, big enough to resist the predicted combination of tension and shear forces, are satisfactory.

Other types of proprietary anchor may be suitable, but their ability to remain anchored into the slab under successive load applications must be demonstrated. This is to prevent minor impacts reducing the fixing capacity without that reduction being apparent before a significant impact. Suitability is often confirmed by tests that repeat the predicted combination of loads four times before application of a failure load to determine the total safety factor.

Setting supporting posts on plinths will enhance durability. Holes drilled for fixings should be positioned to avoid reinforcement. For through-slab holes, diamond drilling causes less soffit breakout than percussion drilling. Sealing the bolt into its hole will help prevent water ingress and corrosion. Using stainless steel components is also advantageous.

Fig 5.18 Failed restraint support – bolt failure



5.6.4 Requirements of long access carriageways

When the vehicle approach length to a barrier exceeds 20m in a straight line (at the ends of the floors or at the ends of ramps), traffic-calming measures must be installed to restrict the vehicle to the specified velocity or the barrier and its primary structure support should be designed to withstand an enhanced impact of at least double the force created by the standard requirement.

5.6.5 Barriers near ramps

Any barrier within 5m of an inclined ramp that could be impacted by a vehicle approaching, on, or leaving that ramp, must be designed to resist half the basic impact force at a height of 610mm.

5.6.6 Protective barriers

The basic requirements, long access carriageway requirements, and ramp requirements should also be applied to internal edges of the vehicle decks, such as at staircases, and at split-level deck edges.

At the internal edges of split-level car parks, deflection criteria may be relaxed, provided designated pedestrian routes do not pass immediately next to the lower deck edge beneath these barriers.

5.6.7 Pedestrian safety

The edge protection must restrain children from accidentally endangering themselves. The provision must therefore be similar to that of balustrades. However, the attraction of barriers and posts for climbing must be taken into account.

The edge protection must not permit the passing of a 100mm diameter ball, and must exceed 1.1m above the top of a separate barrier beam, or the top of the upstand of an integral barrier.

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The design of building services is usually the remit of the mechanical and electrical design consultant. The purpose of this section is to highlight those issues that interface with the structural design. Building services equipment will typically need to be renewed every 15–20 years, i.e. twice or three times during the life of a car park. It should therefore be designed and installed so that it can be removed and replaced without damaging or altering the structure. If it will not be possible to close the car park for an extended period to replace building services plant, the design should allow the car park to be closed section by section for replacing building services plant while the remainder remains operational.

6.1 Lighting

6.1.1 General

Although some car parks may benefit from being partially daylit, it will usually be necessary to provide lighting for continuous use, at least in some areas. It may be possible to make use of daylight for part of the year. The lighting controls can be designed to allow advantage to be taken of available daylight, thus reducing operational costs.

Lighting should be sufficient to assist the safe movement of vehicles and pedestrians and enable staff to carry out their functions. It may also be appropriate to provide lighting of a standard that will help reduce vandalism and crime. The quality of the lighting will have a strong effect on the attitudes of users and will affect both the degree of vandalism and the general care taken with the building (see Fig. 6.1). Lighting has a central role in the UK Safe by Design scheme.

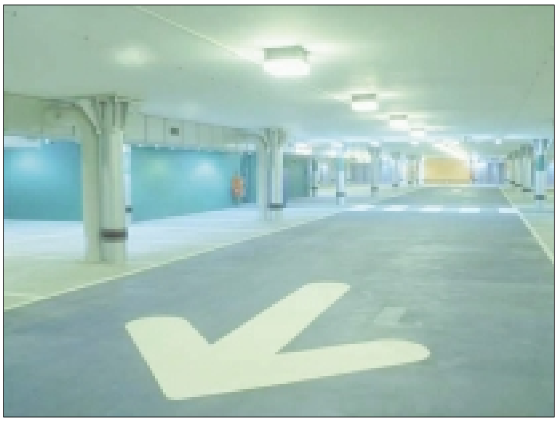

Fig. 6.1 New World Square car park, Cannons Marsh, Bristol – showing a well-lit interior

The nature of car-park structures normally inhibits the scope of the lighting designer, but nevertheless an early association with the architect and structural engineer may produce, within a reasonable budget, a better-considered, visually attractive, easily maintained lighting scheme.

A particular challenge is created in car parks by the low headroom and structural form that make it difficult to provide the reasonably even lighting that would be expected in commercial buildings. Recent research in the UK on acceptable lighting quality for multi-storey car parks has led to a marked increase in recommended uniformity (minimum to average) to 0.40, against a previous recommendation of 0.04.

This followed a major survey of the lighting in multi-storey car parks, which revealed that good lighting could have a major influence on the building's commercial success. Uniformity was considered the most important single factor in subjective assessments of lighting quality.

In addition, high-quality lighting can be a major factor in obtaining acceptance of a multi-storey car park near high-quality or historic buildings. At least one city (Lyons, France) has made high-quality lighting of car parks mandatory as part of a campaign to improve the night-time visual environment.

Colour can be of considerable use in identifying hazards. Unless light sources with poor colour rendering are used, drivers should be able to discriminate between primary colours, though it should be borne in mind that about 10% of males have some form of colour vision deficiency.

Many national lighting codes now require the designer to make assumptions during the design procedure on the maintenance regime to be followed. They are based on designing for a minimum maintained illuminance[6.1]. These assumptions are fed into the calculation procedure. To put it simply, if maintenance standards will be high, less allowance has to be made in the design for dirty luminaires and lamps beyond their design life. It is therefore essential that the client agree on the maintenance regime to be followed before design begins, since the decision has major commercial implications for the car-park operator.

A multi-storey car park can form a major part of the night-time scene in an area and care is needed both to make the structure aesthetically acceptable by means of appropriate lighting and to ensure that light pollution and obtrusive light are kept to a minimum. Avoiding lighting pollution is particularly difficult on open top decks. Environmental zones have been defined from city-centre locations to National Parks and similar, with recommended maximum luminances for each[6.2].

6.1.2 Vehicular areas

Access ramps and routes and parking bays

The appropriate design criteria are usually laid down in national road lighting standards (in the UK BS 5489: Parts 3[6.3], 7[6.4] and 9[6.5]). Typical design illuminances are given in Table 6.1.

Table 6.1: Recommended luminance for multi-storey and underground car parks[6.5]

Area	E_{ave} (lux)	E_{min} (lux)
Parking bays, access lanes	75	50
Ramps, corners, intersections	150	75
Entrance/exit zones (vehicular)	75 night	N/A
	300 day	
Pedestrian areas, stairs, lifts	100	50

A uniformity of 3:1 (average to minimum) should be achieved over most of the area at floor level. One cost-effective approach may be to position luminaires directly over the access routes, since this also helps provide directional guidance for motorists. However, this can cause problems if not supplemented by appropriate extra luminaires, since parked vehicles will cause heavy shadows around the perimeter of the building, providing areas where criminals and vandals can hide and making it difficult to see pedestrians leaving or arriving at their vehicles.

There is a need for particular care in lighting areas where pedestrian and vehicular routes intersect. Vehicle headlights may cause glare for pedestrians and it is therefore essential that the lighting is sufficient to enable them to move safely and be seen by drivers.

In addition to providing light on the road surface, care should be taken to ensure that vertical surfaces such as columns are well lit, especially at corners, bends, junctions and the building perimeter.

Note that UK lighting recommendations are based on UK practice in car park design. In some countries, car park ramps are steeper and curves are tighter. In such cases, the illuminance requirements may need to be increased to allow for the more difficult driving task.

Entrances and exits

By day, exterior illuminances can reach 50,000 lux and can vary widely. Illuminances in entrances and exits by day should therefore be sufficient to minimise the adaptation required of drivers. It may be appropriate to provide for illuminances of up to 1,000 lux. However, at night the interior of the car park may be at a higher illuminance than the street outside. Appropriate controls will therefore be required to adjust the lighting to suit the external conditions. If space is available, daylight louvres over the entrances/exits of the car park can be used to reduce the illuminance contrast.

Appropriate positioning of payment barriers/desks can control vehicle speed at the car park entrance or exit and minimise problems of adaptation for drivers. However, it should be borne in mind that a driver entering a car park on a sunny day will need time to adapt to interior lighting before carrying out transactions with staff or operating ticket-issuing equipment.

Toll booths, barriers and obstructions

Care is needed to ensure that obstructions in the vehicle route are adequately lit for safe driving.

At toll kiosks and ticket-issuing machines, suitable lighting will be required to enable drivers to read instructions, handle cash and tickets, etc. Modern equipment may incorporate internally lit displays and/or Visual Display Terminal (VDT) screens and care will be needed to provide sufficient light for drivers to handle money while avoiding reflections in displays. It may also be necessary to comply with the requirements of the *Health and Safety (Display Screen Equipment) Regulations 1992*[6.6] or equivalent legislation in other European countries implementing the Display Screen Equipment Directive.

Barriers such as those for traffic calming – e.g. 'sleeping policemen' and rising barriers – should be adequately lit for safe driving. Formal standards[6.7] for road lighting of such areas are being developed in some countries.

Any other obstructions in the roadway should be specifically lit to ensure that they are not a hazard to drivers. The direction of lighting should ensure a distinct difference in luminance between the obstacle and its background.

Open top floors

When providing lighting for open top floors of multi-storey car parks, care should be taken not to provide excessive spill light. Although it may appear attractive to mount luminaires at low level, it is difficult to meet uniformity requirements and much light will inevitably be projected upwards, while vehicles will cause problems with shadowing. If column-mounted luminaires are used, types should be chosen with no upward light output.

Care should also be taken that light from this area does not cause nuisance to occupiers of adjacent buildings, particularly in residential areas.

6.1.3 Pedestrian areas

Design should follow the recommendations of the relevant national standards. In Europe, the road lighting code of practice includes relevant information[6.8]. Recommendations may also be included in national interior lighting codes[6.1]. Any pedestrian areas that will be regularly used by staff should be considered as part of the workplace and lit appropriately (see Section 6.1.4).

Particular requirements will apply to staircases, especially where they form part of designated emergency exit routes.

6.1.4 Staff areas

All areas continuously occupied by staff should be lit to a minimum of 200 lux[6.9]. Staff may make use of VDT equipment as part of ticket-issuing or closed-circuit television monitoring. Such spaces should be provided with lighting that complies with the EC Display Screen Equipment Directive or national legislation[6.6]. Guidance is available on complying with the requirements of such legislation[6.10, 6.11].

6.1.5 Emergency lighting

In many countries, it will be mandatory to provide emergency lighting on public pedestrian routes and exit routes used by staff. In Europe, the requirements of EN 1838[6.12] should be followed. However, this has numerous national deviations and is therefore being implemented in most countries as a new edition of the national standard[6.13, 6.14].

6.1.6 Lighting controls

Even if a car park is designed for continuous operation and requires permanent artificial lighting, it will still be necessary to provide lighting controls to enable maintenance to be carried out on specific areas. Also, some countries may have legislative requirements[6.15, 6.16] for lighting controls to minimise energy use.

To minimise the cost of running lighting it may, if a significant amount of daylight enters the building, be worth considering daylight-linked control by means of photocells. Publications[6.17] are available to assist in assessing the amount of available daylight and suitable control regimes.

If the car park is to be used only during specific hours, time-switch control should be considered.

6.1.7 Equipment considerations

Car parks are aggressive environments and all electrical equipment should be chosen carefully to ensure it is suitable. Matters that may need consideration are vandalism, weather resistance, resistance to de-icing salt used on roads, resistance to petroleum compounds (in addition to any electrical safety aspect – see Section 6.4.1) and minimal maintenance.

Recent developments in light sources make it possible to combine high efficiency with good colour rendering. Sources such as metal halide (a high-pressure discharge lamp) now have acceptable lives and good colour rendering combined with colour stability, while being compact and efficient.

6.1.8 Multi-purpose spaces

Increasingly, suggestions are being made that ground floors of car parks can be used for activities such as occasional markets. However, normal car park lighting will not normally be suitable for such situations. If it is known at the design stage that there will be such a requirement, a supplementary lighting installation complying with the relevant provisions of the national code of practice, e.g. the CIBSE *Code for Interior Lighting*[6.1], should be installed. This should have a completely separate control system.

6.1.9 Signs

Positions of signage should be considered at the early design stage so that cable routes for lighting can be incorporated (see Section 6.6). Internal signs should be positioned for maximum visibility; often the sides of structural beams will provide suitable positions. Sign colours need to be chosen after the light sources have been chosen to ensure that colours can be distinguished. Note particularly that high-pressure sodium lamps give little colour discrimination.

Signs can be internally or externally illuminated. Internally illuminated signs need to be positioned where they will not be accessible to vandals. Polycarbonate signs will only provide limited vandal resistance, and most signs are made from brittle plastics.

External signs should comply with the recommendations published by the Institution of Lighting Engineers on maximum surface brightness[6.18].

6.2 Heating

6.2.1 General

The principal heating issue in car parks is associated with the melting of ice and snow. This can be achieved either by using heat to keep the surface temperature above freezing point or by reducing the freezing point by the use of chemicals such as salt. However, designing the car park so that there are no places where water can accumulate on roadway surfaces can eliminate a great deal of the problem.

6.2.2 Ramp heating

In the past, ramp heating has been recommended as a means of dealing with ice and snow. However, experience has shown that it is not particularly effective and should be considered only when other measures such as de-icing chemicals are not suitable. Running costs can be high and, since the heating elements have to be buried in the ramp, any failure will require closure of the car park for maintenance access. If regular icing is expected, it is better to design ramps so that they are not open to the elements.

6.2.3 Open top floors

It is not feasible to provide heating to prevent snow accumulating on open top floors. However, suitably designed falls should permit melted snow to escape and prevent ice forming.

6.2.4 Special provisions for cold climates

In cold countries, it may be necessary to provide heating to protect parked vehicles from damage. A common solution is to use unit heaters, in which case the motors and starting equipment should meet the requirements laid down in Section 6.4.1.

6.2.5 Staff areas

Staff areas continuously occupied should be treated as normal interior spaces and the appropriate guidelines on suitable environmental conditions should be followed. It should be remembered that staff may occupy spaces such as ticket booths for extended periods carrying out largely sedentary tasks, and the environmental criteria should be chosen accordingly[6.19].

6.3 Ventilation

6.3.1 General

Ventilation has to be provided in car parks to avoid the risk of fire and explosion from petrol fumes, and to prevent injury to health from the gases in vehicle exhausts. The most important of these contaminants is carbon monoxide. Since it is almost impossible to extract it locally, the usual approach is to use dilution ventilation.

The physical design of the car park can have a significant influence on ventilation requirements. Entrance and exit tunnels should be as short as possible so that vehicle movement will create adequate ventilation. Their relationship to ticket machines and pay booths should be such that vehicles do not queue in confined spaces. Where possible, pay booths should be in the open, as this will avoid the need for specific ventilation.

Air intakes should be positioned where they will draw in fresh air. The only suitable position may be at roof level. Guidance[6.20] on minimising air pollution at air intakes for office and similar buildings is equally applicable to car parks. If it is not possible to ensure fresh air, this must be taken into account when calculating air change rates.

6.3.2 Carbon monoxide levels

The rate of emission of carbon monoxide by car engines is changing as energy efficiencies increase and 'clean' engines become more common. However, the figures in Table 6.2 have been used successfully for some years for designing ventilation schemes for car parks and may be used unless more accurate statistics are available from vehicle manufacturers or other sources.

Table 6.2: Carbon monoxide emissions

Type of vehicle	Carbon monoxide emitted
5-passenger car	1.47m^3/h (0.41 litres/s)
7-passenger car	2.52m^3/h (0.70 litres/s)

The ventilation rate should be arranged so that the carbon monoxide level in the car park does not rise above the levels in Table 6.3.

Table 6.3: Maximum carbon monoxide levels

Position	Traffic flow	Maximum carbon monoxide level
General car park area	Normal	50 parts in 1 million
	Peak	100 parts in 1 million
Entrance and exit tunnels	Transient occupation only	150 parts in 1 million

It is recommended that the rate of air supply be calculated twice, once using the expected average traffic flow rate and a concentration of 50 parts in 1 million of carbon monoxide and the second using peak traffic flow rate and a concentration of 100 parts in 1 million of carbon monoxide; the higher of the two results should then be used for design.

6.3.3 Natural ventilation

Where car parks are above ground, every effort should be made to take advantage of natural ventilation. However, this will very much depend on the wind speed and direction. Permanent ventilation openings to the external air in the two opposing longer sides can, in favourable conditions, provide sufficient cross-flow ventilation. At each level, openings should have an aggregate area of at least 2.5% of the area of the parking space at that level and be so distributed as to provide effective cross ventilation. This approach may be accepted by building control departments as meeting the legislative requirements.

6.3.4 Mechanical ventilation

For all underground car parks and for those above ground where adequate natural ventilation cannot be provided, mechanical ventilation should be designed so that there is redundancy to allow for maintenance, e.g. three air-handling units where two can cope with the peak demand. Controls must be such that each air-handling plant can be controlled separately and isolated electrically and mechanically during maintenance or repair. A secondary source of electrical supply should be provided fed from a separate supply point. If continuous operation of the car park in adverse conditions is a requirement, standby generation should be provided adequate to provide power to the ventilation equipment at normal loading.

If there are toilets in the car park without direct access for fresh air, they will require a supply-and-extract system on the same lines as for any other internal lavatories.

6.3.5 Noise control

Air-handling plant can be noisy even when well designed. Care should be taken that it does not cause a nuisance to neighbours. A noise survey may be necessary, from which an acceptable maximum noise level can be estimated.

Noise of motor vehicles, especially starting, stopping and on ramps, should also be estimated and any necessary abatement measures taken to prevent it escaping through entrances, exits and other significant openings.

Care should also be taken that noise within the car park is not excessive: hard, reflective surfaces and low ceilings mean that noise generated by vehicle engines may result in levels that can distract drivers.

6.4 Electrical services

6.4.1 Environment

The electrical installation for any areas accessible to the public should be designed to resist weather, fumes and vandals[6.21, 6.22, 6.23]. This will dictate the choice of corrosion-resistant materials designed to thwart the efforts of vandals. Normal national codes of practice (e.g. the IEE *Wiring Regulations* in the UK[6.24]) normally provide suitable guidance.

For areas used only by staff, it may be preferable on aesthetic grounds to use equipment designed for use in normal buildings. However, care should still be taken that suitable equipment is used in any areas where flammable gases may be present[6.21, 6.22].

6.4.2 Design

If continuous operation of the car park is required, the electrical distribution system should be designed with redundancy at all stages from transformers through switchgear, so that operation can continue if any part fails. If standby generation is incorporated, the switchgear should be designed so that generators can be operated individually and in parallel with any part of the main installation. It may be appropriate to size supplies to ventilation plant with spare capacity in case the capacity of the plant needs to be increased during the life of the car park.

Residual current devices should protect all socket outlets except those in 'office'-type areas.

6.4.3 Electrical charging points

It may be considered appropriate to provide charging points for electric vehicles, particularly if the local authority is actively encouraging their use. However, there are at present no general standards for connections between vehicles and shore socket outlets. Vehicle manufacturers should be consulted as to the appropriate facilities to be provided, their positioning relative to parking bays and any special requirements for venting gases.

6.5 Lifts and escalators

Multi-storey car parks will normally be required to satisfy legislation for disabled access and to meet the reasonable requirements of users, e.g. those carrying shopping, children, etc. However, such lifts will normally be unmanned. If possible, the car park should be designed so that lifts can be observed from manned points such as control rooms or toll booths. Closed circuit television may be required. In any case, lifts will need to be as vandal-resistant as is compatible with an acceptable appearance. The balance between aesthetics and vandal resistance will vary considerably between car parks.

Escalators should not be installed where staff are not available to deal quickly with emergencies. They are not a substitute for lifts in complying with legislation on disabled access.

Most lifts require motor rooms. Often, these are above the lift, but some hydraulic lifts have the motor room underneath the lift shaft or to one side. There are specific requirements[6.25] on dimensions of motor rooms and clearance inside the room to allow for maintenance access.

Designing lift installations is a specialised skill, since engineering, traffic flow and aesthetics need to be taken into account[6.26].

6.6 Provision for information technology

6.6.1 Provision for current equipment

Early consideration should be given to the requirements for cable routes for data cables since the form of construction and the limited headroom will otherwise make it difficult to provide suitable routes. Except in staff areas that are, essentially, normal building interiors, all such cable routes should be in trunking to allow access for later changes. Care is needed to ensure that trunking can accommodate the minimum bending radii of the various cables likely to be used, particularly fibre optic cables.

There will usually be a requirement for cable routes:

- from staff areas to ticket machines and/or toll booths
- from control equipment to signs at entrances and exits
- from control rooms to street ducts leading to nearby road signs (car park full)
- for telecommunication operators' lines.

There may also be a requirement for power supplies and control signals for illuminated rooftop advertising signs.

The provision of trunking to serve CCTV and help point positions can be a particularly difficult aspect, since they will usually be at mid or high level and will require careful route planning. It is therefore essential to settle the positions of help points early in the design.

In view of the speed of development of CCTV technology, and the likelihood that the initial installation will be replaced early in the life of the building, long-term best value may well be provided by a comprehensive high-level 'ring main' trunking route with regularly spaced junction boxes from which short links can be made to future camera positions. Particular care is needed to make such high-level trunking vandal-resistant.

Power and data lines should be separated electrically, preferably by separate trunking routes. Guidance[6.27] is available on design criteria for such installations. Alternatively, they can run parallel in multi-compartment steel trunking, provided that suitable cable types are used. Where possible, power and data cables should cross at right-angles.

There may be a requirement for uninterruptible power supplies for computer-based payment systems. This will normally best be provided by discrete units for each item of computer equipment. Such equipment normally requires little maintenance other than occasional servicing of batteries.

6.6.2 Provision for future developments

It is impossible to predict the future except that it will be different. The wise designer will advise the client to install spare cable routes during construction for future use by applications not yet considered. In addition, IT equipment has a very short life, and where possible it is better to provide duplicate cable routes between control rooms, barrier equipment, payment equipment, toll booths, etc. so that a new IT system can be installed while the old remains operational. Once the changeover has taken place, the original cabling can be stripped out without affecting the new system and the cable routes made available for future changes.

Although the types of cable for IT installations are constantly changing, fibre-optic cabling is increasingly being used. The basic requirement for cable routes giving physical protection and electrical shielding are unlikely to change. Fortunately, it appears that in general the physical volume of data cables is not increasing significantly even though the amount of data being transmitted escalates with each new technology.

6.6.3 Induction loops

The positions of induction loops should be decided early so that they can be laid during construction. Slots in decks for induction loops should not be cut after construction, as they can weaken the concrete, reduce cover and even damage reinforcement.

Where possible, induction loops should be laid in conduit with accessible junction boxes, so that they can be replaced in the event of faults without having to cut into the deck.

6.7 Lightning protection

Although not usually the highest buildings in an area, multi-storey car parks should be equipped with appropriate lightning protection. Guidance on design is contained in a British Standard code of practice[6.28], which also contains information on protecting IT equipment against lightning strikes.

Lightning protection can take various forms but will usually consist of a network of copper tapes linking air terminations to buried copper earthing rods. It may be possible to make use of steelwork within the concrete structure as an alternative to copper tapes, but great care is needed to ensure that all relevant joints between reinforcing rods are bonded and of low impedance. It will in any case probably be necessary to bond the lightning protection system to the reinforcement. Bond is also required to other metalwork within the 'separation distance' of the lightning protection network. This will usually include the utility services.

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Fig 7.1 Beam damage from car fire

Fig 7.2 Slab damage from car fire

7.1 General principles

The structure of a modern multi-storey and underground car park is likely to use non-combustible materials and is considered a low fire risk. However, the cars parked in it pose a fire risk. For this reason and the need to provide a means of escape, the recommendations in this chapter need to be considered to limit the impact of a fire and provide means to control it. High fire risk areas and other ancillary accommodation should always be separated from the enclosed car park area to limit the spread of fire. A car park is a designated use. This makes it possible to treat fire considerations in a different way to those adopted for general buildings whose use might change.

Fire spread from vehicle to vehicle is the major concern when considering fire loading in the enclosed car park. The loading will depend on:

- number and mix of vehicles in the car park at the time of a fire, and
- degree of ventilation in the affected area.

Recent research into the growth and spread of fires in closed car parks revealed that there is a risk of fire spreading from car to car, particularly where there is a lack of natural ventilation to the open air or where there is no mechanical extraction system.

Many new cars are constructed of a mix of components that often include synthetic materials. Some modern cars have all-plastic bodywork. Experiments indicate that the danger of spread of flame from a burning vehicle to adjacent vehicles is quite low with steel-bodied motor cars, although tests have not been carried out with plastics-bodied vehicles (see Figs. 7.1 & 7.2). When there is ample cross-ventilation, the fire exposure from a burning car is not intense. In such cases, sprinkler protection may be of assistance in containing a fire. However, the value of sprinklers to steel-bodied vehicles is greatly reduced, as the source of the fire may be shielded from sprinkler heads. While the sprinklers may be ineffective in controlling a fire inside a car, they do reduce the risk of fire developing in rubbish and spreading to a wider area.

There is also evidence to show that, in split-level car park areas, smoke and flames will travel underneath vehicles (see Fig. 7.3) parked at a higher level, thus further reducing the value of sprinkler protection.

Whereas the fire load density in smaller private car parks can be fairly well defined, in commercial car parks a much larger fire load will need to be considered to take account of

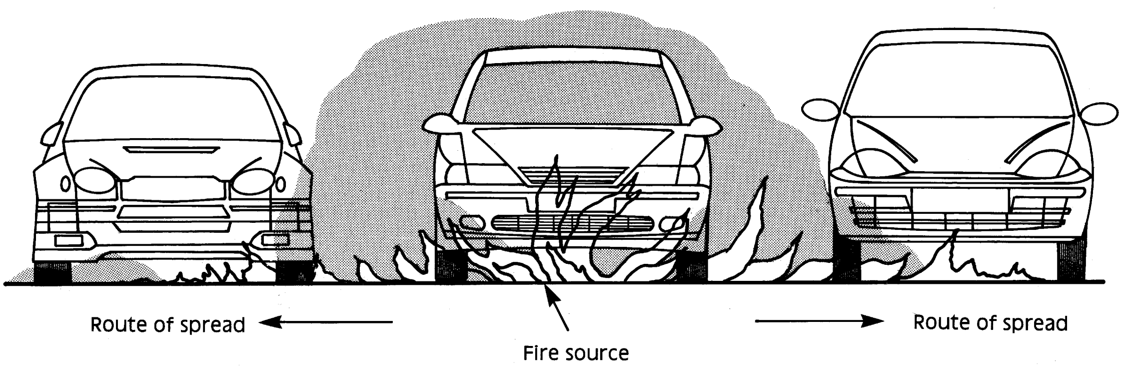

Fig 7.3 Routes of fire spread under cars

unknown factors. Where there may be a risk of free-flowing petrol from a ruptured petrol tank, there may well be an accelerated knock-on effect on adjacent parked cars. Fire hazard should be assessed with input from a specialist in this field.

The provision of ventilation is vital to dissipate smoke and hot gases. In considering escape from car parks, the most critical aspect is often the control of smoke and toxic fumes to give time to escape. This requires allowance for specialist ventilation systems and compartments to provide safe, smoke-free refuges.

Fire safety provisions for a new car park will need to comply with the requirements of the local fire authority. The principles that must be addressed are:

- means of escape
- structural integrity
- prevention of fire spread (both internal and external)
- facilities for fire-fighting
- ventilation and smoke control.

These principles are reflected in the requirements of the local fire authority or building control regulations, for example in England and Wales the *Building Regulations*[7.1] and statutory guidance given in *Approved Document Part B*[7.2]. A specific example is the need to provide sufficient ventilation to enable hot gases and smoke from a fire to exhaust to atmosphere in a controlled manner.

In multi-storey car parks, the fire safety measures required will be governed by the following factors:

- volume of the building
- height of the building
- use of basement construction
- provision for ventilation
- provisions for adequate smoke control
- distance from the boundary or the distance to other buildings
- use category of other parts of the same building or adjacent buildings
- accessibility of the car park to fire-fighting appliances
- spacing and adequacy of fire-protected pedestrian escape stairs
- provision of petrol interceptors (see Section 9.1.6)
- special zoning requirements.

In general, the principles and precedence of issues for fire protection should give the following priorities:

- saving life
- protecting property that may be required under local legislation or for insurance purposes
- preventing fire spreading from one building to another.

The area of fire engineering and provision of equipment generally requires specialist input and advice.

7.2 Specific risks

The risk of cars catching fire is greatest immediately after their arrival in the car park. Another significant risk of fire comes from petrol spillage, which is most likely when a car owner is thoughtless enough to be pouring petrol into their tank. Notices warning against such practices are therefore desirable.

Unfortunately arson cannot be entirely ruled out and measures to improve the general security of car parks help to reduce the possibility of fire through this cause. Supervision and routine maintenance to ensure that no rubbish or other materials are stored in car parks is essential. The advice of the fire authority should always be obtained on fire-prevention measures.

In multi-storey and underground car parks, a number of aspects must be taken into account to control the effects of fire. These include:

- early detection of a fire to safeguard people in the building as well as property
- educating staff who work in the building
- fire warning notices
- reducing fire hazards
- frequent risk assessments
- compartmentalising areas of high fire risk
- providing CCTV
- general security
- measures to limit spread of fire and smoke.

The means for preventing spread of fire by using compartments and provision of fire-resistant boundary walls needs to be considered. Examples of the typical requirements that have to be addressed are contained in the building regulations[7.1,7.3,7.4].

7.3 Fire safety standards

The standard of structural fire resistance required is normally measured in relation to values determined by the fire test described in standards such as the European harmonised fire tests BS EN 1363-1,[7.5] BS EN 1365[7.7] Parts 1–4, and BS EN 1364-1[7.7,], which will supersede BS 476: Parts 20[7.8], 21[7.9] and 22[7.10] respectively. *The Technical Standards[7.11] for Compliance with the Building Standards (Scotland) Regulations 1990 Parts D & E* sets out the mandatory requirements and calls up both the relevant British Standards and the European harmonised fire tests. For England and Wales, *Approved Document B*[7.2] draws on the same references.

The standard of structural fire resistance for multi-storey car parks as a whole or for different parts of the structure must conform to national regulatory requirements and should be agreed with the relevant fire authority. Due account must also be taken of local legislation that may impose additional requirements. For example, Section 20 of the *London Building Acts (Amendment) Act 1939*[7.12], which is principally concerned with the danger of fire in enclosed car parks taller than 30m, imposes additional requirements to those given in the *Building Regulations*[7.1]. Reference may also need to be made to the London District Surveyors Association *Fire Safety Guide No.1. Fire Safety in Section 20 Buildings*[7.13]. There is also further guidance for all enclosed car parks in the *Code of Practice for Ground Floor, Multi-storey and Underground Car Parks*[7.14] published by the Association for Petroleum and Explosives Administration.

The structural form of a car park and general absence of non-structural, fire-resistant finishes, suggest that a fire engineering approach such as that in DD 240[7.15, 7.16] could be adopted. It should be appreciated that a fire engineering approach will not always result in less onerous measures than those arising from prescriptive rules, particularly where there is a lack of adequate ventilation.

The requirement for hydrants, dry risers, hose reels and fire extinguishers should be agreed with the local fire authority. All fixtures and fittings that contribute to the essential safety of people using car parks and which are part of the basic fire resistance of the structure should be designed to be as vandal-resistant as possible.

7.4 Fire detection and extinguishing equipment

7.4.1 General

These recommendations assume that the prompt attendance of the public fire service is assured and that adequate hydrants and an ample water supply are available. Early in the design, it is advisable to discuss all work of this type with the Building Control Body, and particularly the local authority building control where local legislation is applicable.

The fire authority should also be consulted where persons are to be employed to work in the enclosed car park; these may include kiosk attendants, supermarket trolley attendants, maintenance personnel and security personnel.

As automatic detection and extinguishing equipment can be rendered inoperative by explosions or vandalism, it is recommended that hand appliances for use by trained staff should also be provided. Suitable fixed and portable fire-extinguishing equipment to deal with the hazards involved is an essential additional safeguard even when all necessary precautions have been taken in the design of the building structure. In selecting extinguishing equipment, care should be taken to ensure that, while effective for use against petrol and oil fires, the items do not give rise to toxic gases when their contents come into contact with hot surfaces. Some equipment that is suited for use outdoors presents a toxic risk in confined spaces.

Automatic smoke detectors would not normally be installed in car parks because of the risk of false alarms from smoky car exhausts. Programmed beam detectors could provide an answer but may suffer from delays in detection.

Guidance on approved fire-extinguishing appliances should be sought from professional bodies such as the Loss Prevention Council Certification Board.

7.4.2 Sprinklers

As the fuel source is often oil-based, the use and type of sprinklers for car parks have to be carefully considered. In addition, the unoccupied nature of car parks makes the sprinkler heads prone to vandal damage. Any sprinkler system installed should comply with local standards such as BS 5306: Part 2: 1990[7.17] *Fire extinguishing installations and equipment on premises – specification for sprinkler systems.* In cold climates, some sprinkler systems can be rendered ineffective by freezing.

7.4.3 Automatic fire alarms

A fire-alarm system should be installed within the enclosed car park to provide early warning. Provision in enclosed car parks is not always mandatory but is advisable, especially to warn persons in remote parts of the car park.

The fire-alarm system should be installed and maintained in accordance with local standards such as BS 5839: Part 1 1988[7.18]. Where an automatic fire-alarm system is to be installed, consideration should be given to the type of detection, as smoky car exhaust fumes may activate the system.

Owing to the possibility of vandalism, a linear automatic fire alarm system should also be considered. Because this system is hardly noticeable, vandals will not be tempted to interfere with it.

7.4.4 Hand-held portable fire-fighting equipment

Hand-held portable fire-fighting equipment should be installed throughout the car park in accordance with the requirements of the fire authority. Typically this might require fire points not more than 15m from any point in the car park as follows:

Hose reels: Hydraulic hose reels should be provided and so located that at least one nozzle can be taken to any part of the car park. The hose should have an internal diameter of at least 19mm, and the nozzle should have an internal diameter not less than 4.75mm. The water supply should be such as to ensure that the operating nozzle pressure cannot be less than 1 bar.

Foam extinguishers: 9-litre capacity foam extinguishers or 9kg dry powder extinguishers for each 230m^2 of floor area.

Sand buckets: To deal with small fires from spilt petrol, three buckets of sand should be provided on the same basis as the foam extinguishers. Buckets should have lids to keep the sand dry.

European standard EN 3[7.19] makes recommendations for the siting and distribution of extinguishers and on the suitability of the various types for use on different fires. The intervals between routine inspections are set out, along with details of the maintenance regime for each type of extinguisher. Periodical testing by discharge is also covered, including recommended intervals between discharges for the various types of extinguisher:

- water
- foam
- carbon dioxide
- dry powder
- chemical
- sand.

7.5 Means of escape

7.5.1 Statutory controls

Consideration must be given to the requirements of local and statutory bodies and their powers of enforcement. For example, the enforcing authorities throughout the British Isles are the local authorities and the fire authority. Their powers rest in the *Building Regulations*[7.1, 7.3, 7.4] and the *Fire Precautions Act*[7.20] respectively. Local authorities often have additional powers under local legislation, and the fire authority has sweeping powers with regard to fire safety under the *Fire Precautions (Workplace) Regulations 1997 as amended by The Fire Precautions (Workplace) Regulations 1999*[7.21].

7.5.2 Rules for guidance

General

It is always best to enquire of the relevant local and statutory authorities what standards they impose. However, there are some basic commonsense rules that should enable the designer to produce an initial proposal for discussion with the relevant authority.

The principal factors governing escape provision are:

- the number of occupants that may have to escape from the compartment
- the time to travel from any point in the building to a place of safety.

The first of these factors governs the width of exits and the second, because of the effect it has on travel distance, the number of exits. When referring to an exit in terms of escape, it must be an exit from the fire compartment, not just a means of leaving the car park.

The appropriate means of escape should take into account:

- protected routes of escape
- travel distances
- smoke venting
- places of safety
- exits to the street
- fire safety management and warning systems
- segregation of areas of high fire risk

Clearly defined routes must be provided with adequate consideration of:

- exit signage
- fire safety signage
- illumination of escape routes.

It is within these considerations that a proper and sufficient means of escape in case of fire can be designed so that, if fire breaks out, anyone within the car park will be able to vacate the area without outside assistance and reach a place of safety.

Escape routes
Maximum allowable escape distances can be found in such guidance as *Approved Document B*[7.2] of the England and Wales *Building Regulations*[7.1]. Although car parks are not explicitly referred to in Table 3 of the Approved Document[7.2], experience has shown that lower car-park decks are generally treated as 'Storage and other non-residential' for the purpose of horizontal escape. Following such guidance leads to a maximum allowable escape distance of 25m where there is escape in one direction only, or 45m where there is escape in more than one direction. Top decks are usually taken as 'Plant room or rooftop plant – escape route in open air'. This leads to a maximum allowable escape distance of 60m where there is escape in one direction only, or 100m where there is escape in more than one direction. The direct distance to the nearest exit serving a floor area must comply with local requirements.

At least two exits should generally be provided. With split-level car parks, it is normally acceptable if each is provided with alternative exits, one of which should be to a final exit while the others may be by way of an adjoining level to another exit. Travel distances to these exits should be within the limits previously specified. Such exits should be remote from each other and, as far as possible, sited at the extremities of the building to obviate dead ends.

Where site restrictions or practical planning constraints mean a dead end cannot be avoided, it is recommended that the maximum direct distance from a dead end to the nearest exit serving the floor area, or to a point from which escape is available in separate directions, should not normally exceed 12m, provided that the direct distance to the nearest exit does not exceed 30m.

Parking bays and/or service-vehicle loading bays should be laid out with unobstructed access to the exits, which should be clearly visible and well signed.

Width of escape routes
The number of persons likely to use the premises should be assessed, with surge loading taken into account where applicable. In the absence of specific information or guidance from the local fire authority, total occupancy is often assumed to be 2 persons per car-parking space in public car parks and 1.5 persons per car-parking space in private car parks.

The minimum width of any escape route within a floor area and of any exit can then be calculated using formulae in the relevant standards, e.g. Table 5 of *Approved Document B*[7.2].

Table 7.1: Width of escape-route staircase[7.22]

Number of floors	Number of persons one staircase can accommodate		
	1.2m Width	1.5m Width	1.8m Width
1	240	300	360
2	285	360	435
3	330	420	510
4	375	480	585
5	420	540	660
6	465	600	735
7	510	660	810
8	555	720	885
9	600	780	960
10	645	840	1035

Where a ground-floor exit also discharges through a staircase final exit, the latter may have to be increased to the same width. Similarly, where a basement staircase connects to a staircase from above (if permitted), the final exit may need to be widened.

In selecting the width of staircases (see Table 7.1), the design should assume that one of them is out of action within each fire compartment. The width of the remaining staircases within the compartment should then be designed to cope with the full occupancy of the compartment. Guidance can be found in *Pedestrian planning and design*[7.23]. If separate compartments or places of refuge are designed, it may be unnecessary to assume the stair is out of action throughout its entire height. In such cases, adequate protection by a smoke-control system or lobbies on the approach to it will be essential; for example, refer to 5.11 to 5.13 of *Approved Document B*[7.2] for further guidance.

Where the number of persons on any floor area, or to any adjoining split levels, is unlikely to exceed 50, the minimum staircase width could be reduced to 900mm, provided they do not serve more than four storeys.

Where access is provided from a basement storey to a protected staircase serving upper storeys of the building or more than one basement storey of car parking, a protected lobby should be interposed between the protected staircase and the basement storey. The lobby should be ventilated with an opening or shaft direct to the external air not less than 0.4m^2 in area, and any such shaft should be enclosed with fire-resisting constructions to the standards laid down in either the appropriate approved documents of the building regulations[7.1, 7.3, 7.4] or Codes of Practice of the governing bodies such as Section 5.32 and Section 12 of *Approved Document B*[7.2].

Where parking is provided only on the level immediately above or below the vehicle entrance level, one of the required routes of escape may be by way of a vehicle ramp. In that case, however, it is normal to reduce the maximum direct distance permissible to 12m to the foot of the ramp. This is because an occupant is not considered to have escaped from the fire zone until they have reached the other end of the ramp.

A ramp that affords a means of escape should not be steeper than 1:10. If the ramp is also intended as a means of access by disabled persons, it will generally need to be designed with a maximum gradient of 1:12.

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8.1 Concrete durability

8.1.1 General

The exposure conditions for car parks in countries where de-icing chemicals are frequently used are much more severe than those for conventional buildings. The form of the construction will have a significant influence on the severity of conditions that lead to deterioration of vulnerable details. Some elements are in conditions of exposure similar to those in normal buildings for which BS 8110[8.1] or similar exposure classifications are suitable. Evaluation[8.2] of car parks where premature deterioration has occurred has shown that surfaces or details exposed to de-icing salt carried into car parks on vehicles or used for de-icing in the car park need greater protection and/or higher standards than for concrete elsewhere.

In such circumstances, the major corrosion mechanisms that affect the durability of car park structures are:

- corrosion of steelwork and reinforcement caused by the concentration and ingress of chlorides from de-icing salts and coastal environments
- carbonation of the concrete surface leading to loss of alkalinity and hence reduced protection against corrosion.

Sufficient water and oxygen, the two main components required for corrosion, are almost always present in car parks in the UK.

Car parks can also be at risk from freeze-thaw, alkali-silica reaction[8.3, 8.4], sulphate attack, thaumasite[8.5], etc. These are dealt with in standards and specialist guidance. Codes now include requirements which should address some historic problems in older structures, such as HAC conversion, corrosion from the use of calcium chloride as an accelerator or the use of aggregates containing significant chlorides. The remedies available for car parks are the same as for normal buildings and bridges.

Water and salt ingress

A frequent factor in premature deterioration is the retention of water either on rough textured surfaces or in areas of ponding where salts are retained. Evaporation can lead to concentrations of more than ten times the salt content of seawater. The absence of good drainage to carry these salts away and the lack of beneficial rain-wash, on the lower floors, leads to a progressive build-up of salt. Unless there is an effective waterproofing membrane, water carrying the salt can migrate into the concrete. Research has indicated that corrosion of reinforcing steel is initiated at 0.4%Cl by weight. Because this threshold is reduced to 0.1% for prestressing steel, extra care is required to protect it from chlorides. To avoid the opportunity for high chloride concentrations, particular attention to detail is required at joints, interfaces between dissimilar materials or where cracking can occur. This is particularly important at column heads where hidden corrosion of structural connections might lead to sudden collapse. Concrete Society Report TR 22 provides guidance on non-structural cracks in concrete[8.6].

Problems associated with salt attack are much less severe where adequate drainage, movement and construction joints are correctly provided and good compaction of a well-designed concrete mix is achieved. Water and salts will find accelerated passages through poorly designed and leaking joints and through honeycombed concrete surfaces. Good detailing will prevent aesthetic problems with staining, drips and deposits on the floor below and damage to paintwork of cars, which creates operational problems. The major problems from seepage paths arise when the salt ingress initiates local corrosion and loss of section, bond strength and spalling. Cycles of wetting and drying, which are features of car park environments, also act to accelerate the ingress of chlorides into concrete and cracks. Once on the soffit, the moisture is likely to dry, concentrate and be absorbed and, if saline, initiate corrosion. It is good practice to provide a drip detail to prevent seepage through joints, cracks, or over the edges of members, running down the edge of the face and flowing along the soffit. Attempts to stop leakage by sealing the underside of joints or cracks will tend to exacerbate deterioration by trapping moisture and chlorides in the slab.

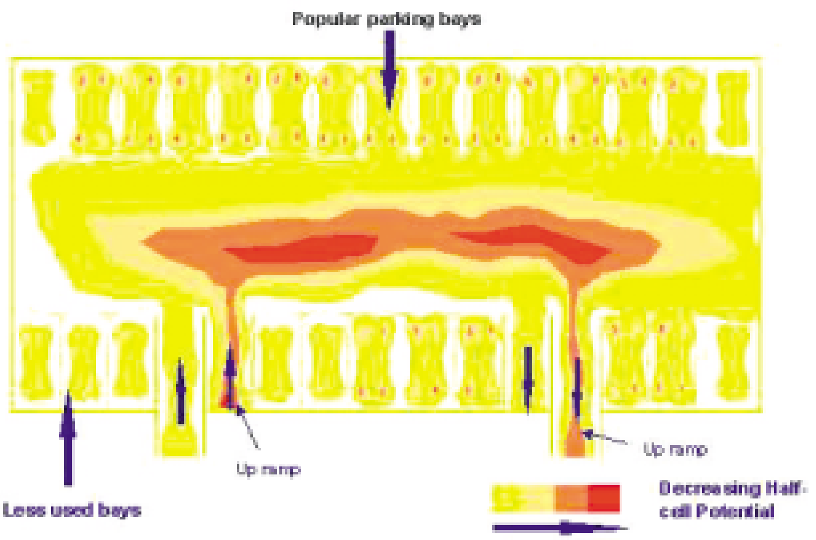

Fig 8.1 Areas of chloride concentration beneath vehicle tracks

Variation in severity

The rate at which the salt builds up in a car park to initiate corrosion varies considerably between mild localities where salting is infrequent, to urban areas with a frequent salting regime. It will also vary with the number of vehicles a day using each space. Analysis of the areas in which chlorides build up to initiate corrosion of the top reinforcement of a slab of a typical unsurfaced car park after about 25 years shows that this is concentrated along the traffic tracks and at wheel positions in the most frequently used bays (see Fig. 8.1).

The extent and value of additional measures to enhance durability appropriate for the usage of the car park should be considered against the cost and disruption implications of maintenance and remedial work during the operational life of the structure. Where de-icing chemicals are frequently used, durability considerations for concrete, steelwork and waterproofing systems to address the above issues must be considered in the design. These issues are discussed further in the following sub-sections.

8.1.2 Durability risk factors

Table 8.1 overleaf summarises the factors that can create risks of premature deterioration in car parks. Actions that can be taken to minimise the problem are discussed in the following sections.

8.1.3 Exposure conditions

Durability recommendations vary between countries and, to draw a comparison, the recommendations in BS 8110[8.1] will be used as a basis for exposure classification.

The conditions of exposure recommended for a car park exposed to de-icing salts are:

- *Very severe* for the top surface of deck slabs and ramps directly exposed to de-icing salts and all faces potentially exposed to runoff or splash
- *Severe* for external reinforced concrete cladding exposed to cycles of wetting and drying
- *Moderate* for the undersides of slabs, beams and columns, which are not directly exposed to de-icing salts and which will not be exposed to runoff or splash containing chlorides (see Fig. 8.2).

These exposure conditions should be considered in conjunction with the options given in Section 8.4.

The recommended minimum concrete grade, maximum water/cement ratio and minimum cover to the reinforcement shall be based on standard design codes such as BS 8110[8.1], BS 8500[8.7] and BS EN 206[8.8].

Concrete for exposed top decks and ramps will be subject to rainfall and other forms of wetting, and is at risk of freezing while wet. In these situations, BS 8110[8.1] recommends using entrained air in all concrete below Grade C50, unless it is protected from wetting by a membrane. The same durability requirements should be applied to structural concrete toppings to precast units. Where reliable supplies of air-entrained concrete are not available, Grade C50 concrete is an appropriate choice.

Intermediate levels of a car park are regularly wetted by rainwater and, in cold regions, by snow brought into the car park either on the vehicles or blown in through open sides; however, freeze-thaw cycles are generally less severe. Local conditions will therefore dictate whether the higher requirements for freeze-thaw are required on intermediate decks in the UK. If frost problems have arisen, they are normally associated with ponding and/or poor-quality concrete. In colder climates, more rigorous measures may be necessary.

Exposure to wind-borne salts from the coast or other environmental conditions may require a higher exposure classification.

8.1.4 Concrete specification

Concrete specifications can be enhanced by a combination of protecting the concrete or reinforcement from chlorides

Table 8.1 : Factors affecting the durability of car parks

Potential problem area	What can be done to minimise the problem
1. Cracking (Note: cracking can be controlled, but not completely eliminated)	• Choice of structural system, e.g. *in-situ*, precast, post-tensioned (see Section 5.3) • Quality control during construction (see Section 10.2) • Design for differential movements (see Section 5.5) • Use of concrete mixes to limit early thermal and long-term shrinkage strain differentials (see Section 8.1.4) • Detailing and construction practice to minimise restrained shrinkage cracking (see Section 8.1.1) • Control of cover to reinforcement (see Section 8.1.5) • Care of reinforcement detailing (see Section 10.2.1)
2. Leaking	• Crack control (see Sections 8.1 and 5.5) • Drainage (see Section 9.1) • Adequate falls (see Section 9.1.1) • Correct installation and maintenance of jointing systems • Protective coatings and sealants (see Sections 8.5 and 9.2.2) • Provision of drips
3. Freeze-thaw damage	• Adequate falls (see Section 9.1.1) • Higher-strength or air-entrained concrete (see Section 8.1.4) • Drainage (see Section 9.1) • Protective coatings (see Section 8.5)
4. Corrosion	• Assessing exposure conditions (see Section 8.1.3) • Quality of concrete (see Section 8.1) • Corrosion protection measures (see Section 8.1.5) • Cover to reinforcement (see Section 8.1.5 and 10.2) • Drainage (see Section 9.1) • Protective coatings (see Section 8.5) • Joint detailing
5. Concrete quality	• Cement type (see Section 8.1.4) • Well-graded fine and coarse aggregates • Admixtures to improve placing and reduce w/c ratio (see Section 8.1.4) • Quality control during construction (see Section 10.2) • Selection of correct concrete grade (see Section 8.1) • Moderate cement content to limit thermal cracking, creep and shrinkage (see Section 8.1.4)

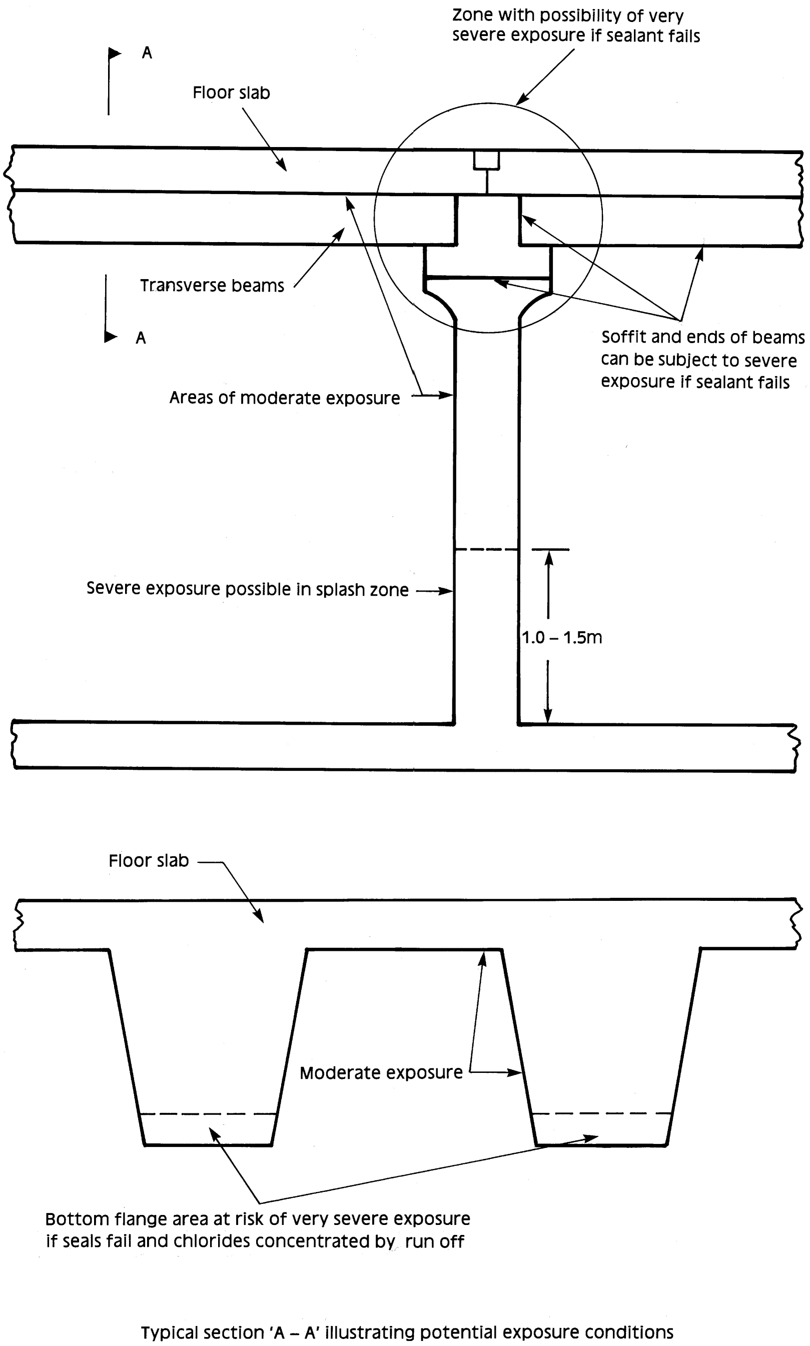

Fig 8.2 Different chloride exposure conditions on a typical beam/column

and/or enhancing the resistance of the concrete to chloride ingress. The extent to which this enhancement is appropriate depends on the:

- severity of salt exposure in the locality and the number of vehicles entering and leaving per bay per day
- balance between increased initial cost and the lifetime costs of maintenance, remedial works, and disruption that is acceptable to the client.

Recent developments in concrete technology have shown that there are a number of ways of enhancing the resistance of concrete to chloride-induced corrosion. Some of these are simple and can be adopted in normal car parks, others are commonly used on major bridge and infrastructure projects, but may be considered for car parks.

Changes in mix composition can significantly improve the durability of the concrete and reduce the chances of premature deterioration. Selecting the right options needs to take into account the local availability of materials and the ability of the contractor to place, compact and cure the concrete to achieve their potential.

The common options for improving the durability of reinforced concrete are summarised below. Care must be taken to ensure consistency of properties when using admixtures or combinations. Changes in elements of a mix can have a disproportionate effect and a high degree of quality control is necessary.

Cement type

For areas of the structure needing good resistance to chloride ion penetration, the base cement should be an Ordinary Portland Cement (OPC), preferably with a moderate tricalcium aluminate (C_3A) content of 4–8%. Sulphate-Resisting Portland Cement (SRC), which has a low C_3A content, should be avoided, as it has less resistance to chloride ion penetration. Where sulphate resistance is required with chloride ingress resistance for ground-bearing slabs, codes allow the use of cement replacement materials (see below) that have better resistance to chloride ion penetration than either OPC or SRC. Alternatively, a polyethylene or other barrier membrane should be used for concrete in contact with the ground.

Cement replacement materials are used increasingly to improve the properties of concrete. The common materials are ggbfs, typically at 50–65%, and pfa typically 25–30% total cementitious content, which have been shown to reduce the rate of penetration of chloride ions into concrete by a factor of 5 to 10 for a given cementitious content and w/c ratio, if well cured. If poorly cured, they have less resistance to carbonation than straight OPC concrete (see Section 10.2.4). Silica fume is another proven cement replacement material but requires particular care in mixing and compaction. Care is needed in using cement replacement materials, as the rate of early strength gain may be lower than for pure OPC mixes.

When cement replacement materials are used, the concrete characteristics for mixing, pumping, compaction, heat evolution, strength gain, finishing, etc. change. Before these materials are used on site, the specialist literature should be consulted and the local availability of the materials and the contractor's experience, equipment and quality control procedures need checking.

Cementitious ratio

Plasticising or superplasticising admixtures enable the water/cementitious (w/c) ratio to be reduced to below the recommended maximum. The rate of strength gain and the ultimate strength can be increased. Lowering the water/cement ratio substantially improves the durability of the mix and particularly the resistance to chloride ingress, but only if it can be fully compacted on site.

Changing one mix parameter can have a desirable effect on one property, but an adverse effect on another. In general, a reduction in w/c ratio can best be achieved by use of admixtures, to prevent a rise in the cementitious content increasing the risk of long-term shrinkage cracking and early thermal cracking.

Concrete durability is substantially enhanced if it has a tightly packed aggregate structure from good grading and shape. Although increasing cement content can offset shortcomings in aggregate characteristics, this can create other difficulties. Evidence from examination of premature deterioration in car parks has indicated that cracking reduces the basic resistance of concrete to chloride ingress. The development of tailored mixes could give a greater strength than the BS 8110[8.1] C50 mix, along with less thermal and shrinkage strains and greater durability. This approach can be considered where specialist experience is available.

Protection against the effects of freezing
Concrete may deteriorate during freezing cycles because trapped water in the surface expands by approximately 9% when it freezes. The volume change causes stresses to develop, resulting in scaling of the concrete surface. To prevent this, an air-entraining admixture may be used. This should have an air content at the point of placement of 5.5% ± 2% for a mix with a 20mm maximum aggregate size. The type and quantity of air-entraining admixture should be selected and batched to be compatible with other admixtures and additives. Alternatively, higher strength mixes in accordance with BS 8110[8.1] can be specified but care is necessary to control shrinkage effects.

Mix development and quality control for durability
Where it is decided to use mixes to resist chloride ingress, trial mixes should be made to determine the best balance of properties for construction, cost effectiveness and durability.

The penetration resistance to chloride ions develops rapidly with OPC and OPC/silica fume mixes and is then almost constant after about one month. Mixes containing OPC with pfa and ggbfs develop even greater resistance over a period of years rather than weeks, providing the concrete is kept damp.

Mixes developed for enhanced durability need quality control based on monitoring the mix composition and site practice in mixing, compaction and curing. While tests on workability and cube strength will provide a check on changes in mix characteristics, the strength criteria and rate of strength gain need to be set at the values established from trial mixes; these may be higher than the minimum values specified by structural strength criteria.

8.1.5 Protection of embedded metals

Corrosion of reinforcement or other embedded metal is a severe problem that may weaken the car park before it has reached its full service life. While modifying or protecting the concrete will achieve most of the improvements in durability, some alternative design considerations can also be considered for the reinforcement.

Cover to reinforcement
When specifying concrete cover, several points must be considered:

- Adequate cover to the top reinforcement in slabs and ramps is essential. Experience suggests that reducing the cover by 10% will decrease the time to activation of the reinforcement by 20%. Increasing the cover significantly can lead to wider surface cracks.
- Care is required in detailing, as tolerances for placing reinforcement, formwork construction, concrete thickness, and finish are sometimes not compatible with the cover tolerance.
- Cover over column and wall reinforcement should be similar to top cover in adjacent slabs, particularly if these are at or near gutter lines or in areas exposed to salt-laden slush and splash.
- Precast members exposed to salts should also have cover requirements at their ends or another equivalent protection (e.g. an impervious coating system).
- Cutting or forming of chases or holes in structural members must not be undertaken without due consideration of the structural and durability implications.

Protecting reinforcement
In addition to high-quality concrete cover, additional protection of the reinforcement can be provided by the choice of steel or by using coatings.

Austenitic 316 stainless steel protects against corrosion in concrete. Because of its cost, it is only appropriate in local areas where conditions are particularly severe, e.g. barrier fixings and bearing shelves. It needs to be detailed to ensure that it is electrically isolated, as any electrical contact between stainless and conventional reinforcement could lead to galvanic corrosion.

Galvanised reinforcing steel has been used increasingly in aggressive environments such as those found in car parks. This coating may offer greater electro-potential compatibility with finishes applied to other components in car parks, such as edge protection (see Section 5.6) but it can be affected by highly alkaline environments, thus reducing its cost effectiveness.

Epoxy-coated reinforcement has been available for use in structural concrete since the mid-1980s. While offering improved protection against reinforcement corrosion, the system relies on the coating being undamaged. Particular care is needed during delivery and site placement to avoid damage.

Protecting prestressing strand
The usually higher quality arising from precast prestressed concrete construction, including higher strength, less permeable concrete and higher precision on cover, has resulted in fewer early problems with prestressed units compared to *in situ* concrete. Where problems have occurred, these are often at the soffit or bearing shelves, where leakage at joints or between precast members has led to corrosion.

A range of problems associated with toppings over prestressed units can lead to leakage. The greater sensitivity of prestressing strand to corrosion makes it particularly important to detail and protect these units, particularly at the cut end faces. The potential problems from the migration of chlorides into hollow-core precast units need to be considered when detailing. Problems with corrosion of post-tensioned tendons, particularly in bridges[8.9], have highlighted the importance of rigorous grouting methods and checks.

Other embedded metals
Electrical contact between dissimilar metals, particularly between uncoated reinforcement and aluminium, stainless steel, lead (sometimes used around drains), brass, copper (also used as flashing materials), and bronze should be avoided. Although these metals are less susceptible to corrosion than steel reinforcement, they tend to promote corrosion of the reinforcement if in electrical contact. It is also important to isolate any galvanised or aluminium elements from the reinforcement to avoid galvanic effects, which can promote premature loss of the galvanised coating or the aluminium element.

Embedded metal conduit for electrical components can adversely affect structural performance and ducts may also become a route for chloride ingress. Steel conduit with insufficient cover will rust and unprotected aluminium conduit can be susceptible to severe corrosion in moist concrete. For these reasons, it is better practice to place metal conduit on the concrete surface. Embedded plastic conduit is an alternative.

Controlling electrochemical corrosion

Cathodic protection of reinforcing steel is frequently proposed for the repair of existing structures rather than being specified for new structures. In extreme exposure conditions, some designers have adopted cathodic protection at the construction stage to stop corrosion starting. For cathodic protection to be effective, all the steel reinforcement in each area must be electrically continuous, with no stray tie wires to short the system. Electrical continuity can be achieved in conventional cage construction, through tie wire and physical contact. If cathodic protection is being considered as part of a long-term maintenance plan, the designers should consider how anode systems can be added that are consistent with the trafficked surface and joints.

8.1.6 Non-ferrous reinforcement

Quality-controlled, pultruded fibre-reinforced plastic (FRP) bars are now available as a non-ferrous alternative to steel bars. Early experience indicates that these materials offer high durability in aggressive chemical environments, including salt and fuel contamination. Design guidance for the use of FRP reinforcement is contained in the IStructE report *Interim guidance on the design of reinforced concrete structures using fibre composite reinforcement*[8.10]. These materials do not require a cement-rich, highly alkaline environment for their long-term protection. Some fibres (e.g. glass) are sensitive to the alkali in concrete and fibres incorporated in polymers can become damaged in the damp highly alkaline conditions of concrete. If such fibres and polymers are to be an effective replacement for steel, care needs to be taken to match thermal effects, stiffness, moisture movement and strain to failure parameters.

8.2 Structural steel

Steel may be used as an alternative to reinforced concrete for framing, in composite design or for concrete-filled steel columns. Where chlorides pose a threat, car park design requires greater consideration than for normal buildings in the selection of steel components and detailing to provide appropriate corrosion protection and to avoid mixing different types of steel or metals leading to bi-metallic corrosion.

Primary requirements of the design are to prevent exposure of the steel frame and steel fixings to direct/indirect salt exposure and impact damage and to meet fire requirements. Where these have been achieved, normal steelwork painting systems for outdoor exposure can be used subject to consideration of fire protection. Where there is a risk of salt exposure, such as at the base of steel columns adjacent to driveway areas, a bridge paint specification may be more appropriate.

Profiled steel sheeting is often used as permanent soffit formwork, acting compositely with the slab. Where there is a risk of chlorides percolating through the slab, particularly in shrinkage cracks, and becoming trapped on this sheeting, corrosion can be rapid. Galvanising will only slightly delay this and such damage is not easily monitored or remedied. For these reasons, additional attention to detail is needed with such systems.

The appropriate level of fire protection to the steel elements in the structure will need to be provided in accordance with normal practice (for example BS 5950: Part 8[8.11]).

Particular problems can arise where steel elements enter concrete – an interface that cannot normally be inspected. The surface layers of concrete become carbonated with time and lose the alkalinity that protects the steel. Chloride ingress at the surface can also initiate corrosion. It is therefore necessary to ensure that the corrosion protection on embedded steel is continued into concrete for at least the specified depth of cover for reinforcement.

Steel corrosion can be particularly severe where cracking develops around the steel creating a downward crevice into which organic matter and/or salts can concentrate. This maintains the damp conditions that accelerate corrosion of bare steel. This accelerated corrosion can also arise with fixings into holes having cavities or with poor-quality mortar infill that rapidly carbonates. Attempts to seal the surface of such a crevice may only trap dampness and hide corrosion developing below. Bolts into the slab or columns for barriers and cladding fixings, etc. are similarly at risk. The choice of details for such barrier and cladding fixings should take into account the ease with which such elements can be removed for inspection and replacement if there is a risk of deterioration.

8.3 Basements and buried structures

The deterioration processes for car park ramps and decks built below ground is similar to that for above-ground structures, as described in Section 8.1, subject to the following specific considerations:

- Soil and groundwater conditions, which may pose a risk of sulphate attack on the concrete.
- Brackish or saline groundwater can be concentrated at the inside face of reinforced concrete walls and base slabs, leading to chloride attack of the reinforcement.
- Bacterially active clay soils can form sulphates and acids by bacterial action and enhanced protection may be required.

The IStructE report[8.12] on basement structures provides comprehensive guidance on other aspects of below-ground construction.

8.4 Concrete finishes

The floor of a car park should be serviceable but not noticeable. Puddles, crude irregularities and stains will attract the attention of the driver and passengers. Although, as the designer hopes, car park users may never notice the floor surface, it can nevertheless have an important influence on the customer's reaction to a car park. Uneven surface finishes will be uncomfortable to walk on in soft-soled shoes. Smooth surfaces have less skid resistance and enhance the levels of tyre noise in turning areas; however, vehicle speeds are low and, even in the wet, skid resistance may not be as critical as in normal highway design. The surface should be suitable for the application of traffic direction and stall markings.

Surfaces of consistently good appearance can only be achieved with consistent materials, timing and surface finishing processes. Even minor changes in day-to-day methods cause irregular textures and patterning that detract badly from the appearance of a floor.

8.4.1 Parking areas

Even when water ponds only occasionally on intermediate floors, blotchy, dusty patches can result after drying out. In the direction of fall, a standard of regularity at least equal to that of floor toppings given in BS 8204[8.13] is recommended. This requires no depression greater than 6mm under a 3m straightedge. Abrupt depressions of any depth should be avoided.

Attaining an acceptably smooth surface is not a separate stage in the floor-casting process. Success comes from placing concrete evenly, compacting it uniformly and controlling the amount of surcharge ahead of the straightedge when striking off. Regardless of the texture specified, finishing should be a separate process that follows striking off. Regularity is largely determined at the striking-off stage, since the finishing techniques can change merely the character of the upper surface. The tamped surface described separately later has frequently been provided on un-waterproofed floors mainly because it tends to disguise irregularities. Surface laitance and puddling are more likely with such a surface and make wheeling trolleys more difficult.

The concrete detailing should take account of the coating system to be used, avoiding sharp edges when necessary. Avoid coating upstands, etc., which may be subject to mechanical abuse from vehicles.

Smooth but unpolished surface

A smooth but unpolished surface is generally required only in areas where waterproofing is to be applied or for forming water-collecting channels. Mention has been made in Section 8.5.3 of the need for the smoothness to be appropriate to the proposed type of waterproof membrane. For a uniformly smooth surface, a float technique may be required but this requirement should be checked with the coating installer. As a minimum, this surface would normally be prepared by vacuum shot blasting before applying the coating, so perfection in the finished surface is not as important as with a plain power-trowelled surface.

Power-trowelled surface

Power trowelling after floating produces a dense, smooth hardwearing surface with negligible ‘ripple’ or ‘chatter’ marks. Such a surface has advantages in terms of drainage and the control of puddling and also in the durability of the surface, the lack of dusting and the resistance to chloride ingress. Although such a surface does have poor skid resistance, it is becoming more popular.

Grinding

As an alternative to wet trowelling, a suitable surface texture for any waterproofing treatment can be obtained by means of a grinding machine. Unlike scabbling, a grinding machine skims the surface to reveal a sound, dust-free and extremely hard face. Grinding cannot correct bad surface textures but can eliminate the early dusting arising from first use of good concrete or improve a heavily dusting surface that was badly cured. Before grinding, the effect on the cover should be checked and alternative measures, such as applying waterproof coatings, should be considered (see Section 8.5). Unless combined with vacuum collection, grinding is a dusty process. The cost is reduced when grinding is carried out between 24 and 48 hours after casting.

Tamped surface

A tamped finish is produced by raising and lowering the compacting beam in its final pass to produce a surface with ridges at a fairly regular spacing of 20mm to 30mm and up to 5mm high. It is difficult to maintain an even distribution of ridges and uniformity from pour to pour. Generally, the grooves should be in the direction of drainage falls and on ramps should follow a chevron pattern. If the tamped finish is too heavy, it will impede drainage and lead to contaminants being trapped in the bottom of the grooves. Because of the lack of compaction in the ridges and the tendency for some residual bleed, this finish can be dusty.

Non-tamped textural finishes

Surface texture for appearance and skid resistance may be applied by roller or by stiff brush. The roller can be a cylinder with projecting studs to produce a pattern of indentations or an open cylinder made with expanded metal to produce a weave pattern. Brush-worked finishes are produced with a stiff wire or bristle brush.

Both types of finish are produced soon after the surface has been smoothed by a compacting beam or straightedge, provided that the concrete does not bleed excessively.

These finishes can suffer from similar disadvantages to the tamped finishes as regards uniformity from pour to pour, drainage and surface durability causing dusting.

8.4.2 Vehicle ramps and circulation areas

Where vehicle ramps are steeper than 1:10, a lightly tamped surface is recommended, with the grooves in a chevron pattern to facilitate drainage. Brushed and smooth surface finishes may not have sufficient traction in wet or icy conditions.

Where vehicular ramp and deck slopes are less than 1:10, power floating followed by brushed or lightly tamped surfaces are considered appropriate.

Surfaces to be waterproofed should be compatible with the waterproofing system used (see Section 8.5).

8.4.3 Pedestrian areas

With the exception of vehicular ramps, all parts of the car park should be suitable for both vehicles and pedestrian use. All designated pedestrian areas should be clearly defined and any finishes should minimise the risk of slipping; for example, some waterproof membranes and surface coatings can be slippery when wet.

8.4.4 Floor hardeners

Many floor-hardening treatments are available, either sprinkled into the concrete before it has hardened, or applied after hardening. These reduce surface dusting and improve wear resistance with varying degrees of effectiveness. Hardeners by themselves should not be relied on to create good, lasting wear-resistance. A suitably constructed concrete floor should not require floor-hardening treatment. On such a floor, the occurrence of dusting depends on the severity of the abrasion, and the acceptability of dusting will vary according to the function of the building. In general, more dusting can be tolerated in a multi-storey car park than in most factory buildings, although this will depend on the maintenance programme as well as the standard for dust prevention set by the car park owners.

8.4.5 Walls, columns and soffits

Smooth, high-quality plain-finished concrete is suitable for walls, columns and soffits. In modern car parks, the surface is often given a decorative or anti-graffiti treatment (see Section 8.5.4). Exposed edges of concrete sections should be chamfered to enhance their appearance and to improve safety. Although cast-in galvanized steel corner guards can do much to protect concrete columns in vulnerable locations, careful detailing is required as the steel corners can be sharp and impose a risk to persons falling. For this reason, their use should be limited.

Concrete upstands should be suitably finished to receive the coating system without blemishes.

Special feature finishes can be used to good effect and can be varied throughout the car park. They should not be abrasive or endanger users of the car park. Where deep profiles are used, the design and installation must be carefully checked to ensure the minimum cover to the reinforcement is maintained.

8.4.6 Basements and buried structures

In general, the finish is similar to walls, columns and soffits but a special feature finish is often used for effect or for directional assistance, e.g. chevrons can be cast into the surface. Special care is required when selecting paint systems for external walls (see Section 8.5.4).

8.5 Membranes and coatings for concrete

Section 8.1 describes various measures for overcoming the natural absorptive qualities of concrete, which result in chloride ions being rapidly drawn into the surface. Bridge decks now have waterproof membranes applied under a protective surfacing and wearing course. Vertical surfaces exposed to spray are often treated with hydrophobic water-shedding materials such as silane. Experience indicates that, where there is good detailing and the waterproofing retains its integrity, these structures are less prone to corrosion.

A deck membrane can be a highly effective means of reducing the risk of chloride-induced reinforcement corrosion providing it is maintained over the life of the car park. For this reason car park membranes for decks and ramps, and protective and cosmetic coating systems for walls and soffits, are being increasingly used for both roof and intermediate levels. To reduce cost, the membranes are generally thinner and more vulnerable to traffic wear and damage than those used on bridges, so it is prudent not to reduce concrete reinforcement covers and concrete quality when they are used.

Decisions on the use of membranes and coatings will usually be based on a cost benefit comparison, but less obvious factors include:

- Membranes and coatings may have to be re-applied in whole or in part every 10–20 years leading to a loss of revenue due to closure of sections of the car park.
- Membranes and coatings can significantly enhance appearance.
- Concrete durability improvements, such as mix changes and enhancements, include both capital costs and on-costs for contractors using difficult or unfamiliar materials and methods.
- Sealants generally have a shorter life than the structure. The relative maintenance cost of the sealants should therefore be taken into account when deciding which method of waterproofing to adopt.
- Even local defects or cracks in joint seals, membranes and coatings can allow chloride ingress and in time corrosion in the concrete below. It is therefore essential to maintain their integrity at all times, if their full value is to be obtained.

These points should be discussed with the client and a strategy agreed as these are long term considerations. Some options for car parks are summarised below.

8.5.1 Concrete decks without a membrane

A concrete deck not intended to be waterproofed with a membrane should be designed and detailed, specified and constructed to drain to prevent standing water.

The positions of construction joints need to be well planned, as they are the points of weakness where leaks may occur.

This approach assumes that decks between joints are uncracked and that any construction joints that open up because of shrinkage or temperature change will be sealed later as part of routine maintenance.

If a concrete deck is not protected by a membrane, salt ingress will in time lead to reinforcement corrosion that will cause damage that is expensive to control and remedy. The time to onset of corrosion cannot be reliably predicted and will depend on the quality of the as-constructed concrete, the amount of salt carried into the car park and the effectiveness of drainage and wash-down procedures.

8.5.2 General deck waterproofing

Car park owners, operators and users all have an interest in preventing water penetrating through roofs and floors of car parks. Water leaking through cracks and failed joints can result in damage to car paintwork, particularly when aggravated by local ponding above. Water passing through cracks in the structure or around features such as holding-down bolts for vehicular restraint barriers, drainage outlets, etc. will lead to rapid deterioration of the structure. Ponding of water may also result in a health and safety issue if it freezes, causing cars to skid or pedestrians to slip.

Special consideration must be given to waterproofing a car park deck that forms the roof to shops or commercial premises. The cost of eradicating water leaks when the car park is in use normally greatly exceeds the additional preventive expenditure required at construction stage.

Where car wash facilities are to be operated inside car parks, decks and joints should be waterproofed and extra provision made for drainage (see Section 9.1.2).

8.5.3 Concrete deck waterproofing by use of a membrane

In addition to its basic requirement, a car park waterproof membrane should have the following properties:

- Capacity to bridge passive non-structural (e.g. plastic shrinkage) cracks that open and close slowly in response to temperature changes, typically 0.5–1mm wide.
- Capacity to bridge live structural cracks (up to 0.3mm wide) which open up after waterproofing and may be subject to rapid cyclic movement.
- Chemical durability and compatibility with adhesion to any joint materials with which it comes into contact.
- Capacity to be bonded to concrete and/or capable of performing unbonded.
- A surface that is skid- and slip-resistant and capable of resisting the abrasion and loadings from vehicular traffic.
- Tolerance to being laid during local weather.

At passive cracks or construction joints, where movement cannot be accommodated by the membrane, it may be necessary to re-bond the crack or joint with structural resin. Care must be taken to ensure the crack will not simply re-form alongside the re-bonded crack. A mastic-sealed formed joint, local reinforcement of the membrane or a proprietary movement joint system terminating the membrane either side of the joint (see Section 9.2) should be provided to deal with the above concerns.

Solar radiation, de-icing salts, fuel and oils, shrinkage hardening and embrittlement can all reduce the life of membranes. Suitable durability test results and/or documented in service performance are therefore needed as the basis for material selection.

Spray-applied and thin membranes
The membrane element of a system for vertical upstands and horizontal surfaces normally has a minimum dry film thickness of 1mm and is formulated to bridge both live cracks and passive cracks. In particular, the thin membrane must be capable of accommodating rapid cyclical movement at low temperatures without splitting.

The concrete surface will need to be finished to a smoothness suitable for the type of membrane to be applied. Some thin membranes require a very smooth surface with no irregularities, whereas others can tolerate small sharp depressions.

As this type of membrane is fully bonded, it is vital that the surface is properly prepared by shot blasting or other similar means to remove all oil, grease, dust and laitance before laying a membrane; this operation is normally the responsibility of the waterproofing contractor. During construction, the type of curing agent used on the concrete should be carefully considered for compatibility with the membrane system. In particular, wax-based systems should be avoided.

The essential properties of a good ductile and resilient membrane conflict with those of a hard wearing surface. A spray-applied waterproofing system normally has at least four layers: primer, waterproof layer, and two coats of wearing surface separated by non-slip aggregate. The first wearing coat should act as a matrix to hold the aggregate in place, while the second encapsulates the aggregate and provides a consistent appearance. Other thin membrane systems are available, e.g. poured/modified epoxy coatings. These normally comprise two layers – a primer and a combined waterproofing and wearing course. The system can be applied by pouring, the wearing course aggregate being broadcast after application. All materials must be compatible with each other and should be tested as a complete system on a concrete substrate.

The final surface finish should be skid- and slip-resistant and ideally available in different light-stable colours to differentiate between parking bays and traffic aisles. It should be checked that the material used for line markings does not adversely affect the performance of the membrane. For this reason, many systems use line-marking materials of the same generic type as the membrane itself. The amount of aggregate in the wearing surface dictates the amount of movement the membrane can take: too much aggregate can reduce the elasticity of the membrane, causing cracking and splitting; too little can lead to softening in hot weather.

Taking account of the above, the surface finish must be designed to withstand abrasion and loadings from pedestrian and vehicular traffic normally expected in a car park designed for passenger vehicles and light vans not exceeding 2500kg. The system should also be capable of dealing with the variable abrasion conditions at turning areas, ramps, aisles, parking bays and kerb upstands. Suitable protection to edges of kerbs, etc. may be required if the membrane is not capable of resisting scuffing from vehicles.

Water vapour trapped in the concrete substrate below the membrane can lead to blistering and debonding in the heat from the sun. When thin membranes are used, it is imperative that there is a path for water vapour to escape. For thin concrete slabs with uncoated soffits, moisture and vapour can escape from below. However, if the slab is thick or has a vapour-proof polyethylene membrane beneath, the surface membrane should be capable of breathing and allowing trapped water to escape without causing blistering.

Mastic asphalt
Traditional mastic asphalt waterproofing can provide a cost-effective solution, provided care is taken during preparation and application. The material is particularly sensitive to reflective cracking and so care is needed to seal passive cracks and fill depressions that could form points of failure.

Mastic asphalt should not be bonded directly to the deck. An underlay of sheathing felt should be used or, for partial separation, a felt or mat of woven glass fibre. On ramps where the gradient is less than 1:10, mastic asphalt can be used provided it is bonded to the concrete. The concrete surface should be prepared by tamping or stippling to provide a key for the asphalt. Special care and detailing is needed at the intersection of ramps and floors.

As asphalt materials can yield under the combined effects of loading and increase in temperature, they are not suitable as a founding layer for impact-resistant barriers. Therefore, consideration should be given to the use of plinths to raise any baseplates and fixings above the level of the waterproofing.

Bituminous materials should not be used with polysulphides, since uncured polysulphide and bitumen are mutually soluble, leaving the cured material weak at the interface; also, tar-based surface treatments are unsuitable over membranes of synthetic rubber. All materials should be checked for compatibility and evidence of successful previous use.

Health and safety
Where membranes are to be applied in confined spaces, fumes can build up and respiratory equipment or forced ventilation may be required. When considering membranes, fire resistance should be taken into account; in the UK, a minimum rating Ext.F.A.A, AB or AC when tested to BS 476 Part 3: 1975[8.14] should be specified.

Warranty
As a minimum, the membrane system should satisfy the following:

- The system should hold an independent test certificate covering the intended use and relevant characteristics when applied to concrete (e.g. EOTA certification or equivalent).
- Ideally the manufacturer should be able to demonstrate the successful application of the system on similar sites that have been in place for at least five years. This should be backed by independent performance-related documentation.

Maintenance
Regular inspection is important to ensure that the waterproofing is fulfilling its requirements. Where required, maintenance/repair should be carried out in accordance with the manufacturer's/installer's recommendations.

8.5.4 Decorative and protective coatings

Good-quality concrete with adequate cover to reinforcement does not require any special paint finish for protection against the normal conditions of exposure. However, car parks are often painted to enhance their appearance and improve the lighting levels. The use of bright colours, painted walls, decks and soffits can do much to obviate dark areas and reduce opportunities for crime.

Decorative coatings

Most decorative paint can be applied by brush, roller or spray. Surface preparation is vital if the finish is to be a success. All surfaces should be clean, dry and free from cracks or defective areas. All cracks and defects should be repaired before treating the surface with a fungicidal wash, if this is required. When the concrete surface is porous, special primers may be needed before the final coat is applied.

Special anti-graffiti paint systems are also available to protect vulnerable areas of the car park: these either form an impervious seal that can be cleaned with solvents or are sacrificial and can be easily removed and replaced.

Protective coatings

These coatings have been specially formulated to resist acidic gases, chemical attack and water ingress. Surface preparation is similar to that for decorative painting, although where anti-carbonation coatings are required it may be necessary to fill blow holes and imperfections before painting.

Intumescent coatings

Intumescent coatings provide fire resistance to steel-framed structures. Consideration needs to be given to the moisture content and preparation of the steel for successful application. Advice should be sought on the suitability of coatings and, in particular, their resistance to abrasion. Accidental damage or vandalism could remove the coating and thus compromise its performance in a fire.

All applied coatings should allow water trapped in the structure to escape without affecting the bond between the coating and the substrate.

The appearance of the car park can be greatly enhanced with deck coatings. Some of these are not full elastomeric membranes and often do not have the same crack-bridging capabilities as the spray-applied or thin, poured epoxy membranes. Such deck coatings would not be expected to be fully waterproof, unless so specified. Such materials offer limited protection against chloride ingress but enhance the environment and dynamics inside the car park.

Deck coatings and decorative paints can be highly effective in maximising illumination and reflectance in basement areas. Appropriate ventilation is needed when applied in confined spaces.

Special consideration is required when painting external basement walls, depending on the water table. If the concrete is likely to be saturated, the paint system must have a low water vapour diffusion resistance if blistering and failure are to be prevented.

8.6 Bearing materials

Bearing materials should be compatible with the anticipated loading and amount of movement. The material specified should be non-corrosive and durable for the service life of the car park. Where there may be a need to replace the bearings, e.g. in the event of a failure or fire, they should be accessible and detailed to facilitate removal and replacement. Bearings need to be configured so that, where there is a risk that joints might leak water and salt, these should not collect on or around the bearing where the solute could be absorbed into concrete.

References

8.1 BS 8110-1: *Structural use of concrete: code of practice for design and construction*. London: British Standards Institution, 1997

8.2 Henderson, N. A. *et al*, eds.: *Enhancement of whole life performance of existing and future MSCP*. London: DETR Project Report, 2002

8.3 Institution of Structural Engineers: *Structural effects of alkali-silica reaction: Technical guidance on the appraisal of existing structures*. London: SETO, 1992

8.4 Building Research Establishment: *Alkali-silica reaction in concrete*. Digest 330 Pts 1–4. Watford: CRC, 1997

8.5 Thaumasite Expert Group: *The thaumasite form of sulphate attack: risks, diagnosis, remedial works and guidance on new construction*. London: DETR 1999

8.6 Concrete Society: *Non-structural cracks in concrete*, Technical Report TR 22, Slough: The Society, 1992

8.7 BS 8500: *Concrete*. London: British Standards Institution, 2002

8.8 BS EN 206-1: *Concrete specification, performance, production and conformity*. London: British Standards Institution, 2000

8.9 Concrete Society: *Durable post-tensioned concrete bridges*. Crowthorne: The Society, 2002

8.10 The Institution of Structural Engineers: *Interim guidance on the design of reinforced concrete structures using fibre composite reinforcement*. London: SETO, 1999

8.11 BS 5950: Part 8: *Structural use of steelwork in buildings: code of practice for fire resistant design*. London: British Standards Institution, 1990

8.12 The Institution of Structural Engineers: *Design & construction of deep basements*, London: The Institution, 1975 (revision in preparation)

8.13 BS 8204: *Screeds, bases and in-situ floorings*, London: British Standards Institution, various parts and dates

8.14 BS 476: Part 3: *Fire tests on building materials and structures. External fire exposure roof test*. London: British Standards Institution, 1975

The investigations carried out on car parks that have begun to deteriorate before reaching their expected life to first major maintenance have often found that poor drainage and joint leakage are implicated. If the decks and ramps are not laid to proper falls that encourage water containing de-icing salt to drain away quickly, chloride ions quickly penetrate the surface. If the falls are correct but the gully designs are such that they block easily or are not maintained, the result will be the same.

Similarly, joints in the ramps and decks must be properly detailed and maintained, otherwise chloride ion penetration will occur at the slab edges or the cut edges of precast beams. In severe cases, water will run along the underside of the slab, which may have been detailed for a less severe exposure (i.e. it was anticipated that the joint would be maintained and so the beam was not expected to come into contact with de-icing salts) and therefore have less cover to the reinforcement.

Correct specification and maintenance of drainage and jointing systems is therefore extremely important for the long-term durability of the car park.

9.1 Drainage

Well designed and properly maintained drainage is essential to ensure that all water deposited on the exposed surfaces is rapidly discharged through an effective drainage system. Standing water is detrimental to both the structure and the operation of the car park. In the UK, drainage is designed to BS 8301[9.1] and BS EN 12056[9.2], and in other countries local standards will apply. Key issues for consideration, beyond those in the standards, are as follows.

9.1.1 Required falls

The specified minimum falls to the finished surface of the roofs and floors are normally based on the following:

- The quantity of water likely to fall on the area under consideration.
- The texture and accuracy of the floor finish.
- The sensitivity of the structure to deflection and creep.
- The anticipated efficiency of any waterproofing.

Unless particularly smooth, plane surfaces with short drainage lengths can be guaranteed, it is recommended that falls in a finished surface should be no flatter than 1:60. This minimum requirement applies to all trafficked surfaces, irrespective of whether the area is covered or exposed – the more generous the fall the greater the ability to shed water and to prevent harmful chloride salts saturating the concrete. User comfort also has to be considered and falls greater than 1:20 or sudden changes in fall should generally be avoided.

The decks in basement and underground car parks should also have a minimum fall of 1:60 to allow for washing down.

9.1.2 Parking areas

The roof is the most exposed area and the drainage should be designed in accordance with local rainfall statistics. In storm conditions, some build-up of water is inevitable and the edges of decks should be designed to contain water and prevent wetting of the decks below. Intermediate floors are wetted by rain blowing through partly open sides and by snow and ice melting on parked cars. The quantity of water deposited on intermediate decks from this source is likely to be about 2 litres per parking space per parked vehicle in the UK; this also depends on the average stay, with shopper car parks having short stays and more water, while commuter/business car parks will often have a full day stay per bay. Proprietary drainage network analysis programs and methods are used to design drainage systems.

Although the direction of fall depends on the geometry of the car park, falls and drainage channels should be designed to suit the type of structure and to take account of any sensitive structural details. Provided the drainage is well designed, it is not essential to lay the fall of the decks outwards towards the exterior of the car park.

Where car-wash facilities are to be operated or allowed inside car parks, allowance should be made for higher than normal discharges of water and salt through drainage channels and associated pipework.

9.1.3 Ramps and circulation areas

Falls towards ramps should be avoided but, if the geometry of the car park does not allow this, drainage paths should be intercepted to avoid water discharging onto the ramps. Adequate drainage should be provided at the bottom of ramps, particularly at roof and entry levels, to remove water swiftly and prevent ponding and possible freezing over. If it is the policy of the operator to periodically wash down all levels or to operate car-valeting services inside the car park, drainage should be provided at the bottom of all ramps.

9.1.4 Pedestrian areas

Where decks are laid to falls, pedestrian areas should ideally be situated at the higher end of the gradient. Staircases, lifts, etc. should be above general deck level or discreet drainage should be provided to intercept water flowing towards staircases and lifts.

Drainage channels, slots and gratings, etc. should be dimensioned to minimise risk to pedestrians tripping and stumbling.

9.1.5 Piped systems

Piped systems should be arranged to be as unobtrusive as possible, both externally and from within the car park. Wherever possible, downpipes should be located on the shielding side of the column to avoid traffic impact and fixed so that they do not encroach into the adjacent parking space. Protective hoops or shielding may need to be provided where it is not possible to use the structure to shield the pipes. Consideration should also be given to the possibility of additional loading on horizontal pipe runs, arising from vandalism.

It is essential to make adequate provision for access and rodding the drainage system. Traps for protection against salt, grit, oil and petrol entering the surface-water disposal system should be provided in accordance with the requirements of the Local Authority.

9.1.6 Interceptors

Interceptors are required to prevent spillages of oil and petrol from entering the main surface water drainage. Petrol interceptors should be outside the car park but if this is not possible they should be in positions that are easily serviceable without disrupting the operation of the car park. Where deep interceptors are located inside the car park, consideration must be given to access and loading requirements for maintenance vehicles.

9.2 Joints

The structural requirements for joints are described in Section 5.5.

In locating and selecting the type of movement joints, account should be taken of the need to maintain drainage falls and to minimise ponding. Ideally, movement joints should run parallel to the drainage falls and preferably be located at the higher end of sloping surfaces.

9.2.1 Proprietary movement joints

Proprietary movement joints should be suitable for trafficked areas but should not impede traffic flow or impose excessive dynamic loading on the structure. Joints in a waterproofed area should be compatible with the system of waterproofing and should be watertight over their entire length, including the ends.

9.2.2 Sealants

Joint fillers and sealants should be compatible with the size of joint, the magnitude of movement, the dynamic effects of traffic, and any spillages during normal use of the car park. Local codes will give suitable joint designs for the range of movement expected; in the UK, design is to BS 6093: 1993[9.3] and the sealant should comply with BS 6213: 1992[9.4].

The material used to seal joints in structures can be conveniently divided into two categories, pre-formed materials and *in situ* compounds. To be satisfactory, both groups should possess the following characteristics:

- For external use and where a waterproof joint is required, the sealant must be, and remain, impermeable over the full range of anticipated movement (see Section 5.5 and Appendix A).
- The joint must be durable, as periodic removal may be difficult and expensive.
- Ideally, the joint should have a similar design life to that of the building, but this is rarely achievable. Consideration must be given to the consequences of and means of replacement.
- It must be bonded to the sides of the groove in which it is inserted. In practical terms, this means that the sealant should bond well to damp concrete.
- As the joint opens and closes, the sealant must deform in response to the movement without loss of integrity.
- It should be comparatively easy to install in all weather and site conditions relevant to the location of the structure.
- Joints used with waterproof membranes should be designed in conjunction with the waterproofing membrane manufacturer. The contractor laying the membrane should also be responsible for providing any joints, to avoid contractual difficulties.

The sealant, whether pre-formed or *in situ*, is normally accommodated in a rebate in the concrete. The shape and dimension of the groove are important in ensuring a satisfactory and durable seal. A rule-of-thumb method for sizing a joint is that the depth of the groove to be filled by sealant should be about half the width, but this depends on the specific materials used. For grooves that are too deep, pre-formed foam beading or similar materials are used to pack out the joint. For butt joints in slabs, provision must be made to prevent the filler material from falling through when the joint is open.

Pre-formed materials

Pre-formed materials are often based on neoprene, which is considerably cheaper than *in situ* systems such as polysulphide and silicone rubber. However, when the cost of accurately forming the joint to receive the pre-formed neoprene strip is taken into account there is usually only a small cost difference.

In situ compounds

In situ compounds are divided into a number of types, the thermosetting materials being the most common.

Thermosetting compounds, chemically curing

Materials in this category are one- or two-component compounds that cure by chemical reaction to a solid state from the liquid or semi-liquid state in which they are applied.

High-grade materials in this class are flexible and resilient and possess good weathering properties; they are also inert to a wide range of chemicals. These compounds include polysulphides, polyurethanes, silicone rubber and epoxide-based materials. They can be formulated to have an expansion-compression range in excess of ± 25% over a temperature range from –40ºC to +80ºC.

While thermosetting compounds are considerably more expensive than mastics and thermoplastics (see below), they accommodate far greater movement and are more durable. Some formulations require a primer on the concrete and it is particularly important to ascertain whether the particular product will bond to damp concrete or whether a dry surface is required. Complete adhesion between the sealant and the sides (but not the base) of the sealing groove is essential for a liquid-tight joint. In the UK climate, it is virtually impossible to ensure dry concrete on most sites.

Thermosetting compounds, solvent release

Sealants of this type cure by the release of solvents present in the compound itself. The principal materials in use are based on such compounds as butyl, neoprene and polyethylene. Their general characteristics are similar to those of solvent-release thermoplastics, but their extension-compression range is lower, at about ±7%.

Mastics

Mastics are generally composed of a viscous liquid binder with added fillers or fibres. They maintain their shape and stiffness by the formation of a skin on the surface and do not harden throughout the material nor set in the generally accepted use of the term. The binders are usually low-melting-point asphalts, polybutylene, or a combination of these. They are used where the overriding factor is low initial cost and maintenance and replacement costs are not considered important. The extension-compression range is small and so these materials should only be used where a small range of movement is anticipated.

Hot-applied thermoplastics

These materials become fluid on heating and on cooling they become an elastic solid, but the changes are physical only and no chemical reaction occurs. Typical are the rubber-bitumen compounds that are used extensively in many countries. As the sealant has to be applied in a semi-liquid state, it is only suitable for horizontal joints; it is used largely for roads and airfield pavements. The movement range that this type of material can accommodate is greater than that obtained with mastics, but is still small compared with thermosetting chemical-curing elastomers.

Cold-applied thermoplastics
These materials set and harden by either the evaporation of solvents (solvent release) or the break-up of emulsions on exposure to air. Sometimes a certain amount of heat is applied to assist workability, but generally they are used at ambient temperature. This type of sealant can accommodate only a small amount of movement; in addition, it hardens with age and suffers a corresponding reduction in elasticity.

9.2.3 Construction joints and non-structural cracking

Unless construction joints are adequately reinforced to prevent opening up due to contraction, it may be necessary to seal the joint, particularly if there is a risk of water ingress and reinforcement corrosion. Similarly, non-structural cracks can open, particularly in response to temperature changes. Although non-structural cracking is an intrinsic feature of reinforced concrete, it nevertheless needs to be controlled to ensure the service life of the car park is maintained. The subject of non-structural cracking is complex and a good summary of the processes is given in The Concrete Society's Technical Report No 22, *Non-structural cracks in concrete*[9.5].

The appropriate treatment for the construction joint or crack depends primarily on its width, the range of expected movement in response to temperature and loading, and future widening of the crack due to long-term drying shrinkage and its restraint (e.g. by connection to solid stair or lift shafts). Where there is doubt about the extent of movement, a period of monitoring using crack gauges could be considered. Typical methods for sealing cracks are:

- where minimal future movement is expected, the crack can be sealed by a rigid, structural resin such as an epoxy injection system.
- where slight movement is expected, non-structural foaming resins based on polyurethane resins can be used.
- where large movements are expected, cracks may need to be cut out to form a groove and then filled with sealant (see Section 9.2.2).

Using a rigid material (e.g. epoxy resin) in situations where large movements are possible may be self-defeating and can even make matters worse. It is to be expected that the concrete will crack elsewhere owing to the movement strains and reinforcement in the slab may redistribute the crack, forming many fine cracks in the place of one large one. The resulting fine moving cracks can be particularly difficult to seal.

References

9.1 BS 8301: *Code of practice for building drainage*. London: British Standards Institution, 1985 (Replaced by Parts 1– 4 of BS EN 752 but remains current)

9.2 BS EN 12056-3: *Gravity drainage systems inside buildings: roof drainage, layout and calculation*. London: British Standards Institution, 2000

9.3 BS 6093: *Code of practice for design of joints and jointing in building construction*. London: British Standards Institution, 1993

9.4 BS 6213: *Guide to selection of constructional sealants*. London: British Standards Institution, 2000

9.5 Concrete Society: *Non-structural cracks in concrete*. Technical Report TR22, Slough: The Society, 1992

10.1 General

The final durability of concrete is often more sensitive to site practice than to the choice of materials used. General statements in specification clauses normally cover these matters. Good practice for concreting works is covered in a number of guidance documents[10.1]. However, in the severe conditions to which car parks can be exposed, a higher quality of construction is needed to achieve a durable structure and the design should contain details that can easily and reliably be constructed to achieve good concrete quality and reinforcement cover. Similarly, the quality of handling and protection of steel members and their coatings will have a significant effect on long term durability.

10.2 Quality issues

As stressed throughout this document, car parks are not 'normal' buildings, but are generally exposed structures. In the UK, this exposure leads to conditions that are in some ways worse than for civil engineering structures such as bridge decks. Despite all the care taken in designing the structure, specifying the cover and concrete mix composition, the final actions of placing the concrete are essential to durability. Lack of attention to detail when placing concrete or premature stripping of formwork can negate the design efforts and produce a structure with poor durability.

For car park construction, and for the slab and ramp decks in particular, the whole workforce should understand the objectives of these recommendations and use high standards of construction practice.

10.2.1 Construction tolerances

The severity of exposure in car parks makes it essential to achieve the specified reinforcement covers within tolerances. The cover to reinforcement can only be consistently achieved if there is adequate tolerance on the reinforcement bending, the formwork and steel fixing and if the reinforcement can be fixed as detailed. Before pouring concrete, checks are recommended to review the following:

- the drawings' buildability before starting construction
- the formwork proposals
- the proposals for steel fixing and in particular the frequency of spacers
- the proposals for placing and compacting the concrete
- the mix design, aggregate selection and curing methods.

Fig 10.1 Example of surface finishes

During placing, it is most important that the finished level of the top surface of the slab or ramp is placed accurately, as it is the cover depth at the top that is most critical with respect to durability. For the top surface, the achieved cover should be checked and recorded by the contractor immediately the concrete is sufficiently stiff. For formed surfaces, the cover should be checked immediately after the formwork has been removed, with immediate action taken to restore cover in the event of non-compliance.

10.2.2 Placing and compaction

Best practice needs to be followed to ensure the concrete is placed carefully, without encouraging honeycombing or segregation, and then vibro-compacted to full consolidation. The contractor should ensure the mix is carefully inspected at the point of delivery for consistency and time in the mixer, before approving for placing.

With air-entrained concrete, estimates should be made of the air loss between the point of delivery and the point of discharge, as it is the air content at the point of discharge into the formwork that is critical for resistance to freeze-thaw action. An adjustment can then be made to the air content measured at the point of discharge for the sake of convenience. The actual air loss should be established at the beginning of each concrete placement as well as each time the placing conditions change.

Mixes with low water/cement ratio and those containing entrained air or microsilica need extra care, as the cohesion is often significantly greater than for more conventional mixes. To achieve full compaction with such concrete, longer vibro-compaction times are required. In addition, because these mixes have little bleed, there is less natural protection against plastic cracking and so special protection may be required before finishing can begin.

Water penetration at joints has an adverse effect on the durability of concrete. Particular attention should be paid to achieve compaction adjacent to construction and expansion joints.

10.2.3 Protection and finishing

Finishing needs particular care to accommodate the needs of grip, application of waterproofing and to give a clean runoff of surface water and salts (see Fig. 10.1). A compromise is often required between the needs to protect, cure and texture the surface. Done properly, this stage is labour-intensive. The timing of the protection, finishing and curing is of fundamental importance if a dense and durable slab top surface is to be produced.

The timing of the finishing operation requires a concrete surface that has begun to stiffen, yet is free from bleed water and has been protected from severe drying conditions so that plastic cracking of the concrete has not occurred. As a minimum during the finishing operations, the slab surface should be sheltered from direct exposure to the sun and rain and protected against the passage of wind over the surface.

Most finishing problems arise from too much bleed water escaping from the concrete and this leads to dusting. In attempting to provide the required finish, the bleed water is often mixed into the top surface, forming a weak, friable top layer, with poor resistance to abrasion. Cloudbursts can have a similar effect if the surface is not adequately protected.

Should rapid moisture loss occur and result in plastic cracking, the concrete can be re-vibrated to seal the cracks, provided the timing is carefully considered. It is not acceptable simply to finish the surface with a tool to drag silt and laitance into the plastic cracks, as such cracks will soon be exposed again by the wearing action of vehicle tyres.

10.2.4 Curing

Immediately the finishing is complete, full curing precautions must be taken. The resistance of concrete to both chloride ingress and carbonation is substantially enhanced if the surface cover layer of concrete has fully hydrated in the period following casting. Normal procedures in building practice are not sufficient to reliably develop this full surface hydration. OPC concretes hydrate rapidly and good surface qualities can be achieved in 3–6 days if water loss from the surface is prevented. Concrete mixes based on pfa or ggbfs need extended curing for full surface hydration and resistance to carbonation to be achieved.

Curing of each area should begin immediately following the start of the finishing operation for that area. Field experience has shown that curing with wet hessian, covered with plastic sheets for a minimum of 7 days, produces good results for concrete cast *in situ*. Experience also suggests that the performance of proprietary curing membranes is less effective than the above methods in reducing the permeability of the cured concrete surface.

Reference

10.1 C&CA *Concrete practice in building construction*. London: Cement & Concrete Association, 1960

It is recommended that the owner/operator of every car park develops a manual setting out the management practices to be followed on the facility. This should be developed with the design team and highlight design features that require special attention. This will be in addition to any documentation required by health and safety legislation and will be for the guidance of car park managers and operatives.

Increasingly, the handover documentation for all new structures includes a file on health and safety that goes part of the way to providing the necessary information for an inspection and maintenance manual. In the UK, such provision is mandatory. The health and safety file should make the task of identifying materials used in the car park much easier, and will normally include reference to any unusual structural, mechanical and electrical facilities and maintenance requirements.

The presence and dangers of working in confined spaces in car parks must be emphasised (e.g. in lift machinery wells) as, notwithstanding the apparently open and ventilated nature of car parks, there is a greater possibility of accumulation of fuel fumes and exhaust gases in voids such as lift pits than in normal buildings.

11.1 Handover information pack

It is recommended that the design team provide the car park operator with an inspection and maintenance manual, covering the particular features of the car park. This should include:

- specifications
- as-built drawings
- detailed records of construction
- checklist of items to be covered by regular inspections.

These documents taken together should provide the information that will be needed for maintaining the structure in the long term and form a part of the health and safety file.

Historically, there have been problems with drawings required for maintenance and refurbishment contracts being unobtainable, illegible when reproduced from microfilm or showing only general arrangement without the reinforcement detailing essential for structural checks.

If computer-based records are used, they will need to be updated to avoid systems no longer being accessible because of software changes. For this reason, hard copy data is also prudent, the information being maintained by the client in the health and safety file. Digitised record photos can be memory-hungry and of variable quality.

The operator of the structure should be advised of the prudence of ensuring there is a single ‘responsible person’ responsible for the safety of the structure. Ideally, this should be a qualified structural engineer with access to all the records on the structure and the responsibility to update them with maintenance reports, details of alterations affecting the structure, and particulars of damage, deterioration and remedial works.

Structures designed to the recommendations in this document should be less likely to suffer premature deterioration than earlier designs. However, when routine inspection eventually indicates developing deterioration, the frequency and types of inspection will need to be reviewed. By inspecting to identify the early signs of developing deterioration (e.g. ponding, cracking, seepage, waterproofing deterioration), cost-effective pre-emptive action can often be taken before a major problem develops.

The initial frequency of inspection and maintenance of the various parts of the structure need to be specified by the design team, taking into account the characteristics of the design and the expected durability characteristics of materials used. Guidance on inspection and maintenance of car parks is available in an ICE report[11.1].

11.2 Structural limitations on modifications and change of use

The structure will have been designed for a specific loading and maintenance regime, which may include some provision for changes in use or modifications. The maintenance manual should make clear any particular limitations that apply to:

- extensions and increased height
- limits on loading for alternative uses and during works in the structure
- limits on surfacing thickness
- planting and landscaping loads
- drilling through elements and opening up (e.g. sensitivity of structure near columns in flat slabs)
- identification of any areas not designed for chloride resistance where salt should not be applied for de-icing
- limits on washing of vehicles, which should only be carried out in areas where a waterproof membrane has been applied
- requirement for cleaning of the decks and ramps and drains, including a regular washing-down at least annually at the end of the winter to reduce the build-up of de-icing salts
- performance of fixings and edge barriers
- zoned areas designated for fuel storage
- areas designated for car washing.

Reference

11.1 Institution of Civil Engineers National Steering Committee on the Inspection of Multi-Storey Car Parks: *Inspection and maintenance management of car park structures – Guidance*. London: Thomas Telford (in preparation).

The serviceability implications of temperature-induced movement and restrained cracking in structures need consideration, as excess joint movement causing leakage and cracking can lead to durability problems. Table A1 illustrates typical components contributing to the design temperature range that may need to be considered. Further guidance can be found in *Concrete bridge design to BS 5400*[A2].

The moments induced in columns by heating and cooling of the top slab relative to slabs below as well as changes in reactions from differential within the top slab, can be significant in flat slab punching shear.

Table A1: Illustrative calculation of temperatures of exposed car park decks

(Refer to BS 5400: Part 2[A1])				
Site	Birmingham, England			
Altitude	Sea level			
Group	4			
Design life	50 years			
Surfacing	50mm asphalt		Dark thin waterproofing membrane	
Thickness	600mm	200mm	600mm	200mm
Minimum shade air temperature (Fig.7)	-19.0°C	-19.0°C	-19.0°C	-19.0°C
Design life adjustment	2.0°C	2.0°C	2.0°C	2.0°C
Effective minimum shade air temperature	**-17.0°C**	**-17.0°C**	**-17.0°C**	**-17.0°C**
Minimum effective deck temperature (Table 10)	-10.0°C	-10.0°C	-10.0°C	-10.0°C
Correction for surfacing	-1.0°C	-1.0°C	-1.0°C	-1.0°C
Actual minimum deck temperature	**-11.0°C**	**-11.0°C**	**-11.0°C**	**-11.0°C**
Maximum shade air temperature (Fig.8)	35.0°C	35.0°C	35.0°C	35.0°C
Design life adjustment	-2.0°C	-2.0°C	-2.0°C	-2.0°C
Effective maximum shade air temperature	**33.0°C**	**33.0°C**	**33.0°C**	**33.0°C**
Maximum effective deck temperature (Table 11)	33.0°C	33.0°C	33.0°C	33.0°C
Correction for surfacing	1.0°C	1.0°C	1.0°C	1.0°C
Actual maximum deck temperature	**34.0°C**	**34.0°C**	**34.0°C**	**34.0°C**
Design average temperature range	**45.0°C**	**45.0°C**	**45.0°C**	**45.0°C**
Maximum design temperature topside (Table 26)	52.0°C	47.0°C	58.0°C	54.0°C
Co-existent underside temperature	36.0°C	34.0°C	35.0°C	34.0°C
Under hot summer conditions, maximum temperature differential across deck	**16.0°C**	**13.0°C**	**23.0°C**	**20.0°C**

Thermal bow for simply supported units should be considered. For a first estimate it can be taken conservatively as:

$$\frac{(\text{coeff. expansion} \times \text{temperature difference} \times \text{length}^2)}{(8 \times \text{thickness})}$$

More detailed guidance can be obtained from bridge design codes, e.g. BS 5400[A1].

In general, steel and concrete frames have a similar coefficient of expansion. This may be taken as $12 \times 10^{-6}/°C$. Certain types of aggregate, e.g. limestone and granite, have lower coefficients of expansion[A3] and could be considered for use as part of the design.

Temperature effects may be introduced into the design as follows:

(a) Ultimate load case: Dead + Imposed + Temperature. $1.4G_k + 1.6Q_k + 1.2T_k$.
(b) Service load case: Dead + Imposed + Temperature. $1.0G_k + 1.0Q_k + 1.0T_k$.

Movement joints must make suitable allowance for the effect on the joint width of the temperature during construction. Some mastic joint fillers may not be suitable for multi-storey car park construction, since their movement accommodation factor is limited. See BS 5400[A1] for more information.

In order that all these issues are considered in a rational way, the following procedure is appropriate for the design process:

(a) Establish proposed basic car park form and elevational treatment, lateral stability system, ramp and stair locations.
(b) Calculate design temperature of top deck frame.
(c) Establish likely mean temperature during construction, and hence the temperature range.
(d) Taking account of both the lateral stability system and any other secondary lateral restraint present, calculate frame movements at elevations and other critical features.
(e) Check that any constrained expansion forces are acceptable.
(f) Check that frame movements are compatible with elevational treatment.
(g) If (e) or (f) are unsatisfactory, either revise layout or introduce movement joints.
(h) If movement joints are adopted, recalculate frame movements.
(i) Re-check that frame movements are compatible with elevational treatment and proposed movement joint details.
(j) Check top deck thermal bowing effects.

References

A1 BS 5400: Part 2: *Steel, concrete and composite bridges: Part 2: Specification for loads*. London: British Standards Institution, 1978

A2 Clark, L. A.: *Concrete bridge design to BS 5400.* London: Construction Press, 1983 (and 1984 supplement)

A3 Harrison, T. A.: *Early-age thermal crack control in concrete.* CIRIA Report 91, London: CIRIA, 1992

Appendix B Acknowledgements of illustrations

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Parking News

Figs. 1.3, 1.4, 1.5, 1.6, 3.7, 3.9, 3.10, 3.12, 3.15

Flowcrete

Fig. 1.2

European Parking Association

Figs. 1.7, 2.4, 3.1, 3.4, 3.14, 3.17

CABE

Figs. 1.8, 5.1

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Fig. 1.9

WSP Group

Fig. 2.1

Dundec Contracts Ltd

Figs. 2.3, 2.7, 2.8(a) and (b), 3.3, 3.6, 4.9, 7.1, 7.2, 10.1

Dundec Contracts Ltd/Meteor Parking Ltd

Fig. 2.2

Corus

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Arup

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APT Skidata Ltd

Fig. 3.8

Composite structures

Figs. 5.10, 5.11, 5.12

J G M Wood

Fig. 1.10

FaberMaunsell

Fig. 8.1

C K Jolly

Figs. 3.11, 3.16, 5.15, 5.16, 5.17, 5.18