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EFFECTS OF ROADS ON WILDLIFE IN AN INTENSIVELY MODIFIED LANDSCAPE.

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Abstract

This paper examines the ecological impacts arising from road networks and the potential ameliorating effects of roadside habitat in a highly modified landscape. A UK focus has been adopted to illustrate the effects of roads in a landscape with a long history of land use and intensive land management where the impacts and the potential for improvement are considerable.

The impacts of roads in the ecological landscape include habitat loss, fragmentation, and degradation. These interrupt and modify natural processes altering community structures and in the longer term, population dynamics. The large number of fauna fatalities each year from road traffic accidents is also of concern. Road verges can however also provide habitat opportunities and restore connectivity in an otherwise fragmented landscape offering potential to offset some of the adverse impacts of the existing road network. This review demonstrates that roads can present both ecological costs and ecological benefits although currently there is insufficient evidence to confirm some of the key theories which relate to the impact of the barrier effects (at population level) or the value of road verges as ecological corridors. In the absence of complete information the full extent of the problems and opportunities cannot be gauged and every effort should be made therefore to enhance the habitat adjacent to existing roads and to constrain further fragmentation caused by the development of the existing road network. Where further construction is unavoidable conditions should be enforced to prevent roads from reducing further the remaining habitats of conservation value and the connectivity between such habitats.

Keywords roads, wildlife, fragmentation, corridor, barrier, environmental impact.

Introduction

The environmental impact of roads is of increasing international interest and concern (Spellerberg 1998). The impacts of roads include habitat loss, habitat fragmentation and habitat degradation which affect wildlife and its habitats both directly and indirectly (Table 1). Much of the debate on the effects of roads on wildlife has focussed on the barrier effect of roads for the larger mammals which have big ranges or undertake seasonal movements over large areas of mainly natural or semi-natural habitat (e.g. Gunther and Biel 1999, Paquet and Callaghan 1996, Andrews, 1990). Less attention has been paid to the impacts of roads as potential barriers or corridors for smaller animals and plants in a more modified landscape with a long history of intensive land use and land management. In the UK, there are around 370,000 km of roadways which pervade the length and breadth of the British Isles. Only in places such as central and northern Scotland, the northern-most parts of the UK, are there any large continuous areas of semi-natural habitat which remain intact; traffic is audible from virtually every location in England (DETR 1998). To illustrate the ecological impacts of roads in an intensified landscape a case study is presented which demonstrates the potential impact of roads on areas of nature conservation.

On the positive side, the road verge can function as a 'green estate' of considerable length. The provision of linear vegetated verge may provide habitat for many species, a feature of particular importance in a landscape with diminishing areas of undisturbed or (semi-)natural habitat. In such landscapes the continuous nature of the road verge may also be important as a connecting route for wildlife between remnant habitat patches.

This paper is concerned with the impact of the road and its verge in an intensified landscape, and the influence it exerts on plants and animals locally. It considers only the major and immediate impacts of roads and does not therefore consider secondary or remote effects such as any stimulus provided for future development etc. in the neighbourhood of the road.

Case study: an analysis of the potential impacts of roads on areas of nature conservation importance in Oxfordshire, England.

A map-based study has been undertaken for the county of Oxfordshire in England to illustrate the potential impact of roads on areas of nature conservation importance in an intensified landscape. All designated Sites of Special Scientific Interest (SSSI) in the county have been assessed to determine site area, the extent of penetration by roads and the length of road within the site. In the UK, SSSIs are selected to protect a high-quality, representative stock of the country's biological, geological and geomorphological resource. This case study therefore provides a good illustration of the degree to which roads affect areas of nature conservation interest throughout the county.

There are 127 designated SSSIs in Oxfordshire, covering a total of approximately 4,150 ha and ranging in size from less than 1ha to almost 500 ha. Seventy-two (57%) of these sites have no road in or adjacent to them (Table 2). Forty-one sites (32%) have a road running along side them but not within, and 14 sites (11%) have at least one road within the SSSI boundary. Thus almost half of the designated SSSIs in Oxfordshire are affected by roads within or adjacent to them. In the recent past 20% of new routes have passed through areas of nature conservation value (English Nature 1993) although it is intended that SSSIs are avoided where practicable, and full consultation is required when there is potential for either direct or indirect damage or when a road is planned within 100m of an SSSI. In this study roads were found in SSSIs of all sizes but a greater proportion of larger sites were affected. In the largest site in this study there were four roads within the boundaries of the SSSI, including the M40 motorway.

The impact of habitat loss and disturbance due to the road can be easily modelled. Assuming a minor road of 5m width, the area lost can be calculated using the measured length of road within the SSSI, and compared to the total area of the SSSI. The literature commonly cites a disturbed or polluted zone up to 5m from the road, and a detectable impact on ecological communities has been shown up to 100m from a road in the UK (Angold 1997a, 1997b). Further calculations were therefore made of the area affected by the road assuming a zone of impact 5m and 100m from the road into the habitat either side (Table 2).

A surface area equal to at least 1% of the total SSSI habitat and as much 10% of the small sites was found to be occupied by roads. In the affected sites the proportion of habitat lost increased with decreasing size of protected area. Taking a minimum 5m zone of impact from the road, 2% of the total area of SSSIs but 30% of the small sites are affected. With a 100m zone of impact only the larger sites retain any undisturbed and almost a quarter of all the SSSIs protected landscape is disturbed by roads. This example demonstrates most effectively the severity of the environmental impact of the road network in a highly fragmented landscape. The overall habitat loss beneath the road surface is itself significant when considered in the context of the ecological importance of these sites (they are irreplaceable) and in the context of the limited remaining area of conservation importance in the UK. The area subject to disturbance and alteration illustrates the fragility of these remant sites in an intensively modified and highly fragmented landscape, and the paucity of any unaffected 'core' area in all but the very largest sites.

Roads and verges from an ecological perspective

An obvious and pervasive effect of roads is the fragmentation of previously continuous habitat. The effects of habitat fragmentation are well documented and include a direct loss of habitat, an increased ratio of edge to habitat, a reduction in patch size and the isolation of remnant habitat (Andren 1994, Spellerberg 1998 see also Canters and Cuperus 1997, Evink et al 1998, Evink et al 1999). Where roads are the fragmenting feature there are additional effects which include the impacts of pollutants, noise, mortality and the barrier effect of an inhospitable linear terrain of indeterminate length. (Angold 1997a, Angold 1997b, Bennett 1991a and 1991b, Evink et al 1996, Reijnen and Foppen 1997, Slater 1995, Spellerberg 1998).

Roads as barriers

When habitats and their associated populations are fragmented into smaller units and the normal interchange between individual species are severed, their long term persistence may be threatened. Small and isolated populations are vulnerable to extinction in heterogeneous landscapes because of inbreeding depression or as a result of stochastic events. Subsequent re-colonisation is a frequent and a widespread phenomenon however (Fahrig and Merriam 1994, Opdam 1990) and some insects and some mammals are thought to occur as metapopulations and survive because of regular dispersal to and re-colonisation of new and vacated patches (English Nature 1993, Hanski et al. 1995, Lankester et al. 1991). However, habitat fragmentation by roads is usually abrupt and often severe and there is frequently a simultaneous reduction in habitat quality and population size. If new constructions fragment an area in such a way as to leave habitat ‘islands' distant, disconnected and small then the remaining populations may not be able to recover (Soule 1987). Roads can impose major barriers to faunal movement, the intensity of the barrier being dependent on the intrinsic nature of the highway and verge (Bennett 1991a, Bright 1993, English Nature 1993, 1996, Mader 1984, Slater 1995, Vermeulen 1994). The effect of roads on specific mammals is well documented (Bennett 1991a, Clarke et al. 1998, Huijser 1999, Korn 1991, Putman 1997 Richardson et al. 1997, Spellerberg 1998, Forman and Alexander 1998). Bennett (1991a) summarised three major factors which influence the permeability of roads: the width of the gap between suitable habitats (clearance), the relative mobility and behaviour of the animal, and the contrast between the 'barrier' (the road surface and sometimes the verge as well) and the adjacent habitat. The speed of the traffic, the size of the species and its dispersal behaviour are also cited as important factors when assessing the barrier effect of a road (Van Langevelde and Jaarsma 1995). Wide roads with high traffic densities restrict animal movement most severely. The largest and busiest roads are generally penetrated only by dispersing individuals or when resources are scarce. Nevertheless, it is not just large roads or busy roads which impede movement; gravel field-tracks can reduce the rate of crossing for ground-foraging arthropods (Mader et al. 1990) and molluscs avoid pathways which lack vegetation cover (Oggier 1997). All roads therefore can present some level of barrier and increase landscape resistance but the influencing factors will vary greatly between species.

Whilst roads may restrict the directional movement of small animals, they constrain movement rather than limit it absolutely. In studies where small mammals have been translocated to the opposite side of the road they frequently return to their home side (Korn 1991, Kozel and Fleharty 1979) and may do so at all times of the day and night irrespective of the traffic volumes (Richardson et al. 1997) but such road crossings may merely indicate that home ranges are confined to just one side of the road. Other studies clearly indicate that the *natural* inclination of small animals is to avoid crossing roads, and to adopt roads as boundaries to their normal home range. No naturally occurring road crossings by woodland rodents (*Apodemus flavicollis* and *Clethrionomys glareolus*) were detected over a five year period by Mader (1984) and road crossings of stenotopic carabid beetles were equally rare. In another extensive trapping study of nearly 600 small (<500g) mammals Oxley et al (1974) found that only 14 out of a total of 651 recaptured individuals (0.02%) crossed roads, and roads which were wider than 30m were almost never crossed by small animals despite inter-trap movements of over 200m.

Clearly, it is not uncommon for medium and large sized animals to cross all sizes of roads (as evidenced by the high number of visible road casualties) but the indications are that like small mammals, their movements are checked by large busy roads. The frequency of road-crossings by medium sized animals e.g. brown hare (*Lepus europaeus*), grey squirrel (*Sciurus carolinensis*), and stoat (M*ustela erminea*) is greatly reduced with increasing road width (Oxley et al. 1974); hedgehogs (*Erinaceus europeus*) generally avoid roads (Huijser 1999), and badger (*Meles meles*) tend to avoid crossing wide roads with high traffic densities (Clarke et al. 1998). All species of deer regularly cross minor roads but home-ranges are often delimited by primary highways and only seasonal dispersal appears to provoke any frequency of movement across larger, more heavily trafficked roads (Putman 1997).

The review of the literature shows that the severity and consequences of the barrier created by roads varies. In an already fragmented landscape the barriers imposed by roads can seriously curtail interactions between conspecific populations, and the limited gene flow which results from this can render small populations vulnerable to inbreeding depression and to stochastic events (Opdam 1990).

Roads as agents of mortality

Mortality rates for many species are often difficult to obtain. Some countries maintain a national database for fauna casualties on roads but the records are generally for a limited number of larger species, and the reliability of these and other estimates produced from extrapolated data can often produce wide-ranging results. For example, annual estimates of bird mortalities in the UK range from 30 million to 70 million (English Nature 1993). The difficulties of accurate recording are not easy to resolve. Many animals which are seriously injured will seek cover and die out of sight and, because of the speed at which corpses of small animals are scavenged and disappear from the road or are crushed and destroyed by passing vehicles, a single daily corpse census can seriously underestimate the death rate of small animals. On a road where 179 toad corpses were counted at dawn all had disappeared by 08.30 hrs; on average, a corpse remained for less than one hour during the daytime (Slater 1995).

Statistics for the number of road-kills in England and the UK are given in various reviews on wildlife and roads (English Nature 1993, English Nature 1996, Slater 1995). Roughly one million wild animals are thought to be killed on roads in the UK each year, including an estimated 29-40% of all amphibians; 5000 barn owls (*Tyto alba),* or 30-60% of UK population; 50,000 badger (*Meles meles*), or 49% of UK population (Clarke et al. 1998); 50-100,000 hedgehog (*Erinaceus europaeus*), or up to 5% of UK population (Morris 1994) and 58% of the UK fox (*Vulpes vulpes*) population (Harris and White 1994). In the New Forest, Hampshire more than 60 deer are reported killed each year and on Cannock Chase, Staffordshire 180 are reported killed annually (English Nature 1996). Unlike mainland Europe there are no British mammals which migrate large distances as part of a seasonal pattern of activity. These figures therefore relate to individuals killed on roads which intersect their normal home territory, or killed crossing roads when dispersing from their natal territory or when roaming during the breeding season.

In contrast to the highly intensified landscape of Britain, continental land masses retain large tracts of continuous high forest and undeveloped areas which support a greater diversity and abundance of animals, and more research effort is consequently focussed on the larger mammal species. Many of these larger species have extensive home ranges and also follow seasonal migratory routes which necessitate crossing many major highways, increasing their exposure and vulnerability to road traffic. In Slovenia, where a stable population of 320-400 grizzly bears (*Ursus arctos)* occupy a range of 5000 km^2 there were 10 reported road deaths in a two year period (Kobler and Adamic 1999) whilst in Yellowstone National Park (an area of 8,992 km^2), there were 8 black bears (*Ursus americanus*) and 2 grizzly bears killed on the roads in a 10 year period (Gunther and Biel 1999). In a Minnesota study, 11% of all known wolf (*Canis lupus*) mortalities were caused by vehicle collisions (Paquet and Callaghan 1996) and, also in the US, there were an estimated 538,000 deer killed on the road in 1991/2. In Sweden 55,000 deer were killed on the road in 1996 and 12,000 were killed by vehicles in Germany in the same year (Putman 1997). Thus on an international scale, roads and traffic are a major cause of death to larger mammals. International interest in these incidents is increased by the animal welfare issue when large animals are struck by cars, and also the frequency of accidents means that the safety of motorists becomes a major consideration.

Factors which increase the risk of faunal road fatalities

Animals with high density in adjacent roadside verges, or which have large home ranges, or which disperse widely are the most frequent traffic victims (Adams and Geis 1983, van

Langevelde and Jaarsma 1995). Medium and large sized mammals are particularly at risk, especially when the emergence of young coincides with high traffic volumes (Oxley et al. 1974). Various species show seasonal peaks in accident rates often with a higher percentage of males being killed (Davie et al. 1987, Mead 1997, Rotar and Adamic 1995, van Langevelde and Jaarsma 1995). This suggests that breeding or dispersal behaviour may be partly responsible but increases in summer time accidents may also be associated with higher summer traffic levels (Moshe and Mayer 1998). Other species at risk of traffic accidents are those which are attracted to or spend a disproportionate amount of time on a road such as snakes which are attracted to the different microclimate of the road by its heat absorbing surface (Spellerberg 1998), and large herbivores which are attracted by the minerals available in rock salt deposited on roads to prevent freezing (Slater 1995). In the UK birds which use roadside verges as a food resource, those which walk rather than fly across the road (such as the moorhen, *Gallinula chloropus),* and corvids which scavenge on other road-kills are particularly susceptible (Mead 1997).

Various factors contribute to the large number of road-related animal deaths (Clarke et al. 1998, Oxley et al. 1974, van Langevelde and Jaarsma 1995) but the predominant ones are traffic density and road width. These two factors directly affect the success, or otherwise, of an animal reaching the opposite side of the road with an increase in either reducing the probability of the animal crossing safely. However very high traffic volumes can, perversely, reduce some threats to wildlife. By suppressing activity in the vicinity of roads and limiting the cross-over rate fewer animals are killed as a result of collisions with vehicles (Verboom 1995). A study of badgers undertaken by Clarke et al (1998) illustrates this effect. It revealed that an increase in badger mortality was proportional to increases in traffic density but only up to a certain traffic threshold above which badgers resisted crossing the road, and consequently the proportional mortality rate fell.

Most accidents involving faunal casualties occur at night, coinciding with an increase in activity for many species and a reduced field of vision for motorists. On English roads the total animal death toll appears to be greater than that in other European countries (English Nature 1993). This may be because English roads are not as straight as those elsewhere, or because many English roads are hedge-lined, or it may be a combination of these or other factors. Generally, the number of deaths is related to and influenced by the local landscape although even the day of the week can be related to the numbers killed. Davie et al. (1987) found that red fox deaths were highest on a Friday or Saturday night when the volume of traffic is also generally higher.

Ecological Impact of Road Fatalities

If road mortalities are high they can impact at the population level. The decline of occupied badger setts by some 30% in the Netherlands during a 20 year period from 1960-1980 is attributed to traffic mortality (van der Zee et al. 1992). Similarly, although in the UK the badger population seems currently able to withstand the loss from road casualties, Clarke et al (1998) believed that if UK traffic volumes rise in line with the Department of Transport predictions the loss of badgers from road mortality in combination with the high level of habitat fragmentation in the UK may lead to future population declines. In a sample population of hedgehogs in the Netherlands, 2% were killed by traffic, and Huijser and Bergers (1995) concluded that an effect at the population level could not be ruled out. Frog and toad populations can be decimated by even fairly low volumes of traffic (Reh and Seitz 1990), and Fahrig et al (1995) suggest that toad populations could be in a state of global decline as a result of the increase in traffic world-wide. Anecdotal evidence from questionnaires distributed to voluntary toad patrol groups in the UK identified traffic increase as the factor considered to be most important in a perceived decline in toad populations (Foster 1996).

Hard information is still lacking for the effect of roads and traffic at the population level (Bennett 1991a). From the available evidence, the population effect appears generally to be at a local level where there are small populations, or for endangered species (Bright 1993). For most species road-kill does not seem to have a significant effect at the population level (Reijnen and Foppen 1997). Munguira and Thomas (1992) found no apparent effect on the populations of butterflies and Putman (1997) reports that the high accident rate of deer and other ungulates is not sufficient to threaten population status. Nevertheless, the mortality rate combined with the barrier effect of roads may become of increasing significance in a patchy and fragmented landscape where local populations are increasingly reliant upon metapopulation function and occasional dispersal of individuals from separated populations.

Road verges as habitat

In ecological terms roadside verges can be classified as edge habitat having extreme length but very little depth. Edge habitat can provide for both the species typical of adjacent habitat types and the specialised species of overlapping habitats (Way 1977). In the UK road verges are frequently separated from the adjacent landscape by hedges and ditches and are often managed differently from the surrounding landscape so they can feature remnant habitat patches and different communities, including plant species that are poorly represented in the locality. The loss of natural and semi-natural habitat has been so severe in the UK this century (English Nature 1993) that roadside verges are indeed becoming increasingly important as an extensive and relatively undisturbed habitat. In the last comprehensive roadside survey in the U.K., Way (1977) recorded 870 of the 2000 different UK plant species, 20 of the 50 species of mammal, 40 of the 200 species of bird, 25 of the 60 species of butterfly, 8 of the 25 species of bumblebee, all 6 reptile species and 5 out of 6 species of British amphibians. Road verges currently comprise almost 1% of the land surface of the UK. It has been estimated that 10% of the land surface of Great Britain needs to be protected in order to ensure that the majority of species will survive (National Conservancy Council 1984) but protection in the form of designated Sites of Special Scientific Interest (SSSIs) only covers some 7% of the land surface at present. Road verges therefore have considerable potential as an ecological resource and are likely to become increasingly important as refuges for wildlife in intensified landscapes. Several roadside areas have already been designated for their distinctive contribution to nature conservation, six as SSSI's, two as Specially Protected Areas (a pan European designation to protect habitats of important species) and one as a National Nature Reserve.

The fauna of road verges in the U.K. is diverse but the habitat is not suitable for all native species. Invertebrates are generally plentiful on roadside verges. In agricultural landscapes, verges provided a periodic refuge for retreating individuals escaping from agricultural treatments in neighbouring fields (Mader 1984). On verges adjacent to heathland, Eversham and Telfer (1994) observed several rare species of beetle which were more numerous on the verge than on a nearby nature reserve. In other situations however where the road verge is markedly different form the adjacent habitat (as in the case of adjacent woodland) 'interior' species may avoid penetrating the verges altogether (Mader 1984) and, for some carabid beetles the roadside can act as a sink habitat (Pulliam 1988) with populations maintained only by continuous immigration (Vermuelen 1994). Road verges and the central reservations can support a wide variety of butterflies including rare species. On road verges in Hampshire and Dorset, 27 species of butterfly were recorded, representing 47% of butterflies species found in the UK. The range of suitable breeding habitat, the width of the verge and the abundance of nectar were factors which positively influenced the diversity and abundance of species, whilst the volume of passing traffic is apparently no deterrent to breeding moth and butterfly species (Munguira and Thomas 1992). Birds may be attracted to road verges for foraging or occasionally for breeding especially when the surrounding landscape is unsuitable for these purposes. Eighteen different species of birds were recorded as using various sections of the roadside verge in one Danish study (Laursen 1981). Skylarks (*Alauda arvensis*) were the most abundant species and were found to forage more frequently on the road verge than in adjacent fields. They were also found to favour the roadside as a nesting site when adjacent fields provided inadequate cover early in the nesting season. Where open fields were the predominant landscape cover, passerines such as the greenfinch (*Carduelis chloris*) and starling (*Sturnus vulgaris*) were observed to travel long distances to feed on road verges. However, on busy roads the noise levels had a negative effect on bird densities and it is possible that birds only breed on the sub-optimal road verge habitat because of over-capacity or lack of more suitable habitat rather than because it is a preferred nest site. Further population level research is needed to determine the role of the verges in population dynamics of these species. The undisturbed roadside areas also provides habitat for large numbers of small mammals and birds, especially for edge and generalist species (Forman 1995) with a corresponding increase in the number of predator species (Dawson 1994).

Road verges as movement facilitators

Paradoxically, whilst roads may be the source of much habitat fragmentation they may also be a mechanism by which to restore connectivity in an intensive landscape. Due to their linear nature, roads and their verges frequently cross environmental and topographical contours (unlike 'natural' corridors) and can link a range of different habitats thus facilitating biotic movement through an otherwise unsuitable landscape. As a means of retaining and/or enhancing connectivity, corridors, which connect habitat patches and so facilitate the movement and dispersal of animals have been widely promoted (Beier and Noss 1998, Harris and Scheck 1991, Loney and Hobbs 1991, Merriam 1991, Saunders and Hobbs 1991). It is argued that corridors can enable colonisation and re-colonisation and thus prevent local extinctions from accumulating into more widespread and irreversible extinctions.

Getz et al (1978) were able to show that voles (*Microtus pennysylvanicus*) extended their range by some 90 km through utilisation of the verge of an interstate highway and the roads connected to it, implying a corridor function for some species in certain conditions. Several recent works have shown the use of roadside verges as habitat (Downes et al. 1997, Eversham and Telfer 1994, Vermeulen 1994) and Nicholls and Margules (1991) contend that if corridors provide habitat which can maintain populations then it is possible to infer that they may also provide a dispersal corridor which would permit re-colonisation following patch extinctions.

Nevertheless, the 'corridor' theory is not without controversy and its critics assert that corridors are limited in their application, that there is no evidence to show that species cannot do without them and that there is a lack of empirical data in support of the theory (Bonner 1995, Dawson 1994, Rich 1994, Simberloffe et al 1992). Furthermore, there is a risk attached to corridors insofar as if they fail to provide a throughway to favourable habitat at a reachable distance they may function as a sink habitat whilst at the same time depleting the source population (Pulliam 1988, Saunders and Hobbs 1991, Vermeulen 1994). There is also the risk of invasive species or disease moving along corridors to areas that would not otherwise be affected (Hess, 1994).

Traffic assisted dispersal

Vehicles can act as a non-selective means of conveyance, capable of carrying and dispersing organisms over considerable distances. Vehicle tyres and mud flaps are capable of transporting the seeds and propagules of all roadside plant species (Lonsdale and Lane 1994, Schmidt 1989), particularly small, fast growing species (Hodkinson and Thompson 1997) with dispersal being greatest in the direction of traffic flow and with small seeds being carried the furthest (Scott and Davidson 1985). Although largely ignored in the literature, there is also the potential for assisted transport of fauna by vehicles (Bennett, 1991a). Invertebrates frequently enter vehicles and may be transported long distances and, if there are unconfirmed reported incidents in the UK of domestic cats occasionally travelling long distances inadvertently after climbing into the undersides of cars, it is not unlikely that small animals such as rodents may also hitch an unintended lift on occasions.

Management Considerations

Improving the nature conservation value of roadside verges

Responsibility for roadside management in the UK is divided between the Highways Agency (motorways and all purpose trunk roads) and the various local highway authorities (all other roads). The motorway network includes in its 'green estate' 18,000ha of grassland which, until 1975, was sown with a standard high productive grass seed mix and mown regularly. Current policy for the management and maintenance of all primary highways reflects a combination of safety and fiscal measures tempered latterly with the recognition of the potential contribution of road verges to the natural wildlife resource. The present policy for motorways and most other main roads is to plant native species on verges and to cut only sight lines and access areas. Between 1962 and 1990, 33 million trees plus a further 2 million each year have been planted on the motorway 'green estate' in the UK.

In many areas the change to less intensive verge management has produced a closed rank sward with a deep thatch, resulting in an abundance of coarse grasses and umbellifers with no opportunities for sward diversity, especially where fertility is high (Parr and Way 1988, Sangwine 1990). The Countryside Survey of 1990 (Barr et al. 1990) shows that overgrown eutrophic verges which feature umbellifers and stinging nettles (*Urtica dioica)* are now the most common type of roadside vegetation. However, the reduction in roadside verge cutting which has been largely responsible for this, means that there is a concomitant reduction in the level of disturbance and this favours small mammal species as well as giving significant management cost savings. In contrast to the frequently observed mediocre, eutrophic verges, there are some notable plant communities (as denoted by their status as SSSIs) flourishing at the roadside, as well as a number of uncommon and red data book species such as thistle broomrape, (*Orobanche reticulata*) and Watling street thistle (*Erynigium campestre*). Barnsley Metropolitan Borough Council (1995) reports that the undisturbed grass verge supplies nesting opportunities for the declining grey partridge (*Perdix perdix)* in an otherwise limited surrounding habitat due to farming intensification, and a refuge for slow worms (*Anguis fragilis*), badger (M*eles meles)*, and adder (*Vipera berus*).

In the Netherlands, where the intensity of the road network equals that of the UK, road verge management policy has also changed, largely in response to ambitious national targets for nature conservation and de-fragmentation. Management is designed to be sensitive to nature conservation and, as a result, endangered plant species of the Netherlands such as wild parsnip (*Pastinaca sativa*) oxeye daisy (*Leucanthemum vulgare*) and sheep's bit (*Jasione montana*) are thriving on the verges, as are sand lizards (*Lacerta agelis)* and viviparous lizards (*Lacerta viviparta*) (Bekker et al. 1995).

Roadside linear habitats not infrequently accommodate faunal and floral species of conservation interest but uncommon species require uncommon habitats and they therefore may not thrive in habitats managed for species-richness. To optimise the nature conservation value of roadside habitats different management strategies appropriate to the ecological needs of specific target species are required. Inevitably, habitat that may be suitable for one species may be inimical to another. It is necessary therefore to recognise the importance of the management and treatments of the roadside verge and to make early decisions about the desired outcome for the area.

Buffer zones

Buffer zones can be used to prevent degradation of core habitat and to reduce the undesirable effects of edge (Angold 1997a). They can be established beside roads by increasing the width of the road verge and softening the transition from adjacent habitats by planting or by natural regeneration. Broadening the road verge will provide a margin between the road and any adjacent core habitat and at the same time may assist linear movement along the verge, providing habitat or refugia. Road verges often have high levels of species diversity but this may be at the expense of other, arguably more desirable features. Wider road verges clearly increase the available habitat and thus encourage a greater abundance of species which favour that particular habitat type, as well as providing a buffer zone between core habitat and road-associated pollutants. However, although rare species are found on roadside verges it is invariably the common species which contribute most to the roadside composition. An increase in the road verge area which results in a greater loss of the original habitat and its associated flora and fauna should always be avoided. It should also be taken into account that where broad road verges are responsible for an increase in faunal abundance there may be a consequential increase in mortality rates from roadside accidents.

Improving the safety and permeability of roads

Allowing a severed habitat to extend to the verge on each side of the road will reduce the clearance between favourable habitats and facilitate crossing whether or not mitigation measures such as bridges, tunnels or culverts, designed or adapted for wildlife use are employed. The conflict arising from this approach is that an increase in cross-over and a reduction in sight lines along the perimeter of the road can both contribute to increases in mortality. If the barrier effect of roads is to be reduced then both an increase in the safety and an increase in the permeability of roads needs to be considered. Reduction in traffic volume and speed in conjunction with a reduction in the width of the road will both substantially contribute to ‘defragmentation’ of habitat and increase ecological safety. On minor roads, a concentration of traffic on a limited number of roads is considered preferable from an ecological viewpoint to diffusing traffic across the network (van Langevelde and Jaarsma 1995). Greater permeability of the road has been achieved in many European countries in recent years through the provision of ‘eco-passages’ (a generic term for artificially constructed underground or over-ground passageways designed to facilitate faunal movement across roads). In the Netherlands more than 60 constructions have been introduced on new roads in the last 10 years (Bekker et al. 1995) and in the UK, a 40 mile stretch of the newest motorway, the M40, features 14 badger tunnels (Hepinstall and Blood 1993).

The monitoring of eco-passages has shown that they are used by many different animals (Bekker et al. 1995) although their overall effectiveness in terms of reducing mortality and promoting interaction between sub and meta-populatons is still being studied. The extent to which location affects their use by different species, and the behaviour of animals when confronted by passageways (which will determine whether or not they accept and use them) also requires further investigation (Nieuwenhuizen and van Apeldoorn 1995). It is generally agreed that to be effective wildlife passages should be designed with particular species in mind and meet specified criteria; tunnel dimensions, for example, can greatly affect usage (Janssen et al. 1995). However, even with good design not all animals will use the smaller passages especially when the underground passages have to traverse long distances as, for instance, under motorways. The alternatives are to construct viaducts, to tunnel the road or construct 'green' bridges. Green bridges or eco-ducts have been used in many European countries but the cost of installation either during initial construction, or of retrofit following construction can be prohibitive. There are few UK examples - the bridge across the M25 connecting Epping Forest on the outskirts of London is an exception.

There is now widespread use of roadside fencing to prevent animals from wandering onto the roads and, when properly erected and maintained fences are successful in reducing animal mortality (Rotar and Adamic 1995). The greatest reductions in road casualties are realised when fences are used to funnel animals towards a tunnel or eco-passage entrance and prevent crossings elsewhere. The drawback of fencing is that whilst preventing mortalities it can virtually eliminate crossover requiring an extensive network of eco-passages if habitat connectivity is to be maintained. In Austria the fenced road network is almost total and effectively divides the country into 14 habitat fragments; 543 eco-passages are presently installed to improve the permeability of the fenced road network (Volk and Glitzner 1998).

Environmental Impact Assessment and Mitigation

The road building programme in the UK continues but at a rate and scale greatly reduced to that envisaged in the early 1990's. Nevertheless, it is likely that new roads will continue to have a consequence in environmental terms. Environmental impact assessment (EIA), established by statute in the UK in July 1988 for all major road projects (there is no equivalent for existing stuctures), is now a well established procedure and takes account of factors which may prove damaging to wildlife and the natural surroundings. The EIA process is required to critically examine proposals for new developments and to recommend measures to avoid or ameliorate any adverse impacts arising from the proposed scheme but the effectiveness of the procedure is considered by some, to be less than satisfactory. Direct habitat loss is quantifiable and easily considered by the assessment process but issues such as fragmentation, the barrier effect, wildlife mortality and the provision of wildlife corridors are more controversial and the EIA procedure (allegedly) not only fails to be comprehensive in its account of impacts but, the response to fragmentation is perceived as being determined often by cost rather than appropriateness (Kirby 1997). The lack of routine testing of the predictions made in Environmental Assessments and the absence of long-term monitoring and after-care procedures for areas affected by, or established as a result of, construction is also considered to be disappointing (Cibien and Magnac 1998, Janssen et al. 1995, Marshall et al. 1995, Therivel and Thompson 1996).

Guidance on the most appropriate methods to adopt in terms of mitigation for roads is not straight-forward because at present, evidence to support different approaches is incomplete.

Also, many of the impacts will be habitat or species-specific, and therefore there can be no all-purpose answers applicable to every situation. However whilst awaiting further evidence and scientific knowledge, some general principles do apply. English Nature (1993) suggests that comprehensive mitigation should pay attention to:

- avoidance of the best and non-recreatable sites;
- provision of acceptable mitigation, and preferably compensation, for all other habitats affected;
- scheme enhancements by habitat creation on roadsides or elsewhere, re-connection of severed patches and improvement of poor quality habitat links;
- a long term commitment to manage and maintain the mitigation package. Long-term management and monitoring, and attention to the roadside habitat and its management, is an essential aspect of highway maintenance.

CONCLUSIONS

New roads will inevitably lead to habitat loss and fragmentation. The ecological impacts will depend on the nature and extent of the existing road network, and the degree to which natural and semi-natural habitats are already fragmented and isolated by intervening land use. The case study has shown that in the intensively used landscape of the UK, roads affect almost half the designated sites of special scientific interest for nature conservation. Even when roads do not directly destroy habitat the noise and disturbance associated with them may impact significantly on those species which require an undisturbed and/or interior habitat. In the case study it was shown that up to 25% of protected areas may be disturbed by their proximity to a road and that habitat loss beneath roads and habitat alteration near the road are proportionately greater where habitat fragments are smaller, as in an intensively used landscape.

Roads will act as barriers to movement or agents of mortality for some species. With habitat fragmentation movement of individuals through the landscape becomes increasingly important if populations in small habitat patches are not to become increasingly isolated, and therefore vulnerable to genetic change and stochastic events which may jeopardise their long term persistence. In a highly modified landscape the evidence suggests that some species respond by becoming increasingly sedentary so that isolation by habitat fragmentation is intensified by genetic and behavioural modifications of the species. Conversely, if faunal movement continues despite ever increasing traffic densities and without further provision for safe passage, traffic fatalities will be an inevitable consequence which may in itself depress populations of certain species. Roads, and the phenomenal increase in traffic levels in recent years, are a relatively new evolutionary pressure and the effects of this new selective pressure have yet to be fully understood.

There are still many gaps in our current knowledge about the processes which operate within a heterogeneous and fragmented landscape. In the context of roads, research has so far largely considered the effect of roads upon individuals and species (Table 3), this leaves major questions over our understanding of the impacts of roads on biodiversity at the population and community level. These questions can only be addressed by long-term population studies which will enable an understanding of population dynamics in relation to the effects of roads and the efficiency of mitigation and compensation measures. Areas to which further research needs to be directed include: the impacts of fragmentation on populations, the value and effectiveness of corridors, the value and effectiveness of eco-passages at population level, the implications of traffic related mortalities at a population level and an accumulation of data on mortalityies. General autecological and synecological work needs to consider patch dimensions and configuration, the effect of disturbance, dispersal behaviour and an assessment of remedial measures designed to offset the adverse effects arising from both existing and future road construction.

In the absence of this research, it is sensible to apply the precautionary principle to avoid irreversible losses of biodiversity arising from irreparable habitat fragmentation. Alongside this it will be necessary to maintain the existing pattern and connectivity of the remaining natural and semi-natural habitats. Possible natural corridors and migration routes should be protected, and the creation of new or artificial barriers avoided. Engineering improvements or alterations to existing roads can be used as an opportunity for environmental audits and for ecological improvements through the inclusion of further mitigation, compensation and/or enhancement measures, at minimal cost. A methodology to audit the ecological aspects of existing roads is needed in order that we might sustain the nature conservation values in and around them, and identify potential for ecological enhancement and where existing habitat is fragmented by a road, measures created to improve connectivity and reduce landscape resistance are required.

If the damaging effects of the road network are to be moderated an informed dialogue with planners and developers based on a thorough understanding of the long term effects of roads on wildlife is required. Without empirical evidence and its communication arguments for a change in approach and practice will be unconvincing and financial stringency will invariably dictate acceptance of the least-cost method. This will have inevitable adverse consequences, and the process of decline, already apparent for many species may be exacerbated and additional species put at risk. With the correct strategies in place adverse impacts can be minimised and the ecological potential realised.

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REFERENCES

Adams, L.W. and Geis, A.D. 1983. Effects of roads on small mammals. Journal of Applied Ecology **20**:403-415.

Andren H. 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. Oikos **71**:355-366.

Andrews, A. 1990. Fragmentation of habitat by roads and utility corridors: a review. Australian Zoologist **26**:130-141.

Angold, P.G. 1997a. Edge effects in fragmented habitats: the implication for nature conservation. Pages 32-39 *in* K. Canters, editor. Habitat fragmentation and infrastructure. Proceedings of the international conference on habitat fragmentation, infrastructure and the role of ecological engineering, MECC, Maastricht, 18-21 September 1995. Ministry of Transport, Public Works and Water Management, Delft, the Netherlands.

Angold, P.G. 1997b. The impact of roads upon heathland vegetation:the effect on plant species composition. Journal of Ecology **34**:409-417.

Barnsley Metropolitan Borough Council, editor. 1996. M1 junctions 35 - 38. Landscape ecological appraisal. Highways Agency, London.

Barr, C.J., Bunce, R.G.H., Clarke, R.T., Fuller, R.M., Furse, M.T., Gillespie, M.K., Groom, G.B., Hallam, C.J., Hornung, M., Howard, D.C. and Ness, M.J. 1990. Countryside Survey 1990.

Main Report. A Report prepared for the DoE by Institute of Terrestrial Ecology and the Institute of Freshwater Ecology, components of the Natural Environment Research Council. Volume 2. Department of the Environment, London

Baur, A. and Baur, B. 1990. Are roads barriers to dispersal in the land snail *Arianta arbustorum?* Canadian Journal of Zoology **68**:613-617.

Beier, P. and Noss, R.F. 1998. Do habitat corridors provide connectivity? Conservation Biology **12**(6): 1241-1252.

Bekker, H., Hengel, V.D.B. and van der Sluijs, H. editors. 1995. Natuur over wegen. Nature over motorways. Ministry of Transport, Public Works and Water Management, Delft, Netherlands.

Bennett, A.F. 1991a. Roads, roadsides and wildlife conservation: a review. Pages 99-118 *in* D.A. Saunders and R.J. Hobbs, editors. Nature conservation 2: the role of corridors. Surrey Beatty & Sons.

Bennett, A.F. 1991b. What types of organism will use corridors? Pages 407-408 *in* D.A. Saunders and R.J. Hobbs, editors. Nature conservation 2. The role of corridors. Surrey Beatty, Chipping Norton,NSW.

Bonner, J. 1995. Wildlife's road to nowhere. New Scientist **143**:30.

Bright, P.W. 1993. Habitat fragmentation - problems and predictions for British Mammals.

Mammal Review **23**(3/4): 101-111.

Canters, K.J. and Cuperus, R. 1997. Fragmentation of bird and mammal habitats by roads and traffic in transport regions. *in* A. Coope and J. Power editors. Species dispersal and land use processes. Proceeding of the sixth annual IALE (UK) conference, held at the Unversity of Ulster, Colraine 9th-11th September 1997. IALE (UK) Aberdeen, Scotland, UK.

Cibien, C., and Magnac, M.-P. 1998. Etudes, recherches et mesures en faveur de la faune sur le reseau routier: etat des lieux et propositions. *in* Paper presented at the 3rd conference, route et faune sauvage., Strassbourg.

Clarke, P.G., White, P.C. and Harris, S. 1998. Effects of roads of badger *Meles meles* populations in south-west England. Biological Conservation **86**:117-124.

Davidson, A. W. 1971. The effects of de-icing salt on roadside verges. Journal of Applied Ecology **8**:555-561.

Davie, J.M., Roper, T.J. and Shepherdson, D.J. 1987. Seasonal distribution of road kills in the European badger (*Meles meles*). Journal of Zoology **211**:525-529.

Dawson, D., editor. 1994. Are habitat corridors conduits for animals and plants in a fragmented landscape. English Nature, Peterborough. (English Nature Report no. 94)

DETR 1998. Transport Statistics for Great Britain 1998. HMSO, London.

Detwyler, T. R. 1971. Man's impact on the environment. McGraw Hill, London.

Downes, S.J., Handasyde, A. and Elgar, M.A. 1997. The use of corridors by mammals in fragmented Australian eucalypt forests. Conservation Biology **11**(3,3 June):718-726.

English Nature. 1993. Roads and nature conservation. Guidance on impacts, mitigation and enhancement. English Nature, Peterborough, Denise Ramsay (ed).

English Nature. 1996. The significance of secondary effects from roads and road transport on nature conservation. English Nature Research Report 178. English Nature, Peterborough.

Eversham, B.C., and Telfer, M.G. 1994. Conservation value of roadside verges for stenotopic heathland Carabidae: corridors of refugia. Biodiversity and Conservation **3**:538-545.

Evink, G., Garret, P., Zeigler, D. and Berry, J. editors. 1996. Trends in addressing transportation related wildlife mortality. Publication FL-ER-58-96, State of Florida Department of Transportation, Tallahassee, Florida.

Evink, G., Garret, P., Zeigler, D. and Berry, J. editors. 1998. Proceedings of the international conference on wildlife ecology and transportation. Publication FL-ER-69-98. State of Florida Department of Transportation, Tallahassee, Florida.

Evink, G., Garret, P. and Zeigler, D. editors. 1999. Proceedings of the third international conference on wildlife ecology and transportation. Publication FL-ER-73-99. State of Florida Department of Transportation, Tallahassee, Florida.

Fahrig, L., and Merriam, G. 1994. Conservation of fragmented populations. Conservation Biology **8**(1):50-59.

Fahrig, L., Pedlar, J.H., Pope, S.E., Taylor, P.D. and Wegner, J.F. 1995. Effect of road traffic on amphibian density. Biological Conservation **73**:177-182.

Farmer, A. M. 1993. The effects of dust on vegetation – a review. Environmental Pollution **79**:63-75.

Fehlberg, U. 1994. Ecological barrier effects of motorways on mammalian wildlife – an animal protection problem. Deustch Tierarztliche Wochenschrift **101**:125-129.

Fluckiger, W., Oertli, J. J., and Fluckiger-Keller, H. 1978. The effect of wind gusts on leaf growth and foliar water relations of aspen. Oecologia **34**:101-106.

Forman, R.T.T. 1995. The ecological effects of roads and the 'spatial solution' for land mosaics. *in* K. Canters, editor. Habitat fragmentation and infrastructure. Proceedings of the international conference on habitat fragmentation, infrastructure and the role of ecological engineering, MECC, Maastricht, 18-21 September 1995. Ministry of Transport, Public Works and Water Management, Delft, the Netherlands.

Forman, R.T.T. and Alexander, L.E. 1998. Roads and their major ecological effects. Annual review of Ecological Systems **29**: 207-231.

Foster, J. 1996. Toad Patrols: a survey of voluntary effort involved in reducing road traffic-related mortality in amphibians. Froglife Report No1.

Foster, A. C. & Maun, M. A. 1978. Effects of highway de-icing agents on *Thuja occidentalis* in a greenhouse. Canadian Journal of Botany **56**:2760-2766.

Getz, L.L., Cole, F.R. and Gates, D.L. 1978. Interstate roadside as dispersal routes for *Microtus pennysylvaticus.* Journal of Mammalogy **59**:208-212.

Gunther,K. and Biel, M, 1999. Reducing human caused black and grizzly bear mortality along roadside in corridors in Yellowstone National Park *in* G.L. Evink, P. Garrett, and D. Zeigler editors. Proceedings of the Third International Conference on Wildlife Ecology and Transportation. FL-ER-73-99. Florida Department of Transportation, Tallhassee, Florida.

Hanski, I., Pakkala, T., Kuussaari, M. and Lei, G. 1995. Metapopulation persistence of an endangered butterfly in a fragmented landscape. Okios **72**:21-28.

Harris, L.D., and Scheck, J. 1991. From implication to applications: the dispersal corridor principle applied to the conservation of biological diversity. Pages 189-220 *in* D.A. Saunders and R.J. Hobbs, editors. Nature Conservation 2: the role of Corridors. Surrey Beatty & Sons.

Harris, S., and White, P., editors. 1994. The red fox. The mammal society, London.

Hepinstall, C.T.K., and Blood, J.D. 1993. M40 Oxford to Birmingham route location and design. Pages 21-32 *in* Road Panel: Proceedings of the Institution of Civil Engineers and

Transport. Volume 100, Paper 10024.

Hess, G.R. 1994. Conservation corridors and contagious disease: a cautionary note. Biological Conservation **8**(1):256-262.

Hodkinson, D.J. and Thompson ,K. 1997. Plant dispersal: the role of man. Journal of Applied Ecology **34**:1484-1496.

Huijser, M.P. 1999. Human impact on populations of hedgehogs *Erinaceous europaeus* through traffic and changes in the landscape: a review. Lutra **42**: 39-57.

Huijser, M., and Bergers, P.J.M. 1995. The mortality rate in a hedgehog (Erinaceus europaeus) population: the relative importance of road kills. *in* Habitat fragmentation and infrastructure.

Janssen, A.A.A.W., Lenders, H.J.R. and Leuven, R.S.E.W. 1995. Measures combating the effect of habitat fragmentation on the badger (*Meles meles*) in the Netherlands: ecological corridors or pitfalls? *in* K. Canters, editor. Habitat fragmentation and infrastructure. Proceedings of the international conference on habitat fragmentation, infrastructure and the role of ecological engineering, MECC, Maastricht, 18-21 September 1995. Ministry of Transport, Public Works and Water Management, Delft, the Netherlands.

Jones, P. H. 1981. Snow and ice control and the transport environment. Environmental Conservation **8**:33-38.

Jones, J. A. and Grant, G. E. 1996. Peak flow responses to clearcutting and roads in small and large basins, Western Cascades, Oregon. Water Resources Research **32**:959-974.

Kirby, K.J. 1997. Habitat fragmentation and infrastructure: problems and research. *in* K. Canters editors. Proceedings of the international conference on habitat fragmentation, infrastructure and the role of ecological engineering, MECC, Maastricht, 18-21 September 1995. Ministry of Transport, Public Works and Water Management.

Kobler, A. and Adamic, M. 1999. Brown bears in Slovenia: identifying locations for construction of wildlife bridges across highways. *in:* Evink, P. Garrett, and D. Zeigler editors. Proceedings of the Third International Conference on Wildlife Ecology and Transportation. FL-ER-73-99. Florida Department of Transportation, Tallhassee, Florida.

Korn, H. 1991. Rapid re-population by small mammals of an area isolated by roads. Mammalia **55**:629-632.

Kozel, R.L., and Fleharty, E.D. 1979. Movements of rodents across roads. The southwestern naturalist **24**:239-248.

Lankester, K. van Apeldoorn, R., Verboom, J. 1991. Management perspectives for populations of the eurasian badger *Meles meles* in a fragmented landscape. Journal of Applied Ecology **28**:570-573.

Laursen, K. 1981. Birds on roadside verges and the effect of mowing on frequency and distribution. Biological Conservation **20**:59-68.

Loney, B., and Hobbs, R.J. 1991. Management of vegetation corridors: maintenance, rehabilitation and establishment. Pages 299-311 *in* D.A. Saunders and R.J. Hobbs, editors. Nature Conservation 2: The role of corridors. Surrey, Beatty & Sons.

Lonsdale, W.M., and Lane, A.M. 1994. Tourist vehicles as vectors of weed seeds in Kakadu National Park, northern Australia. Biological Conservation **69**:277-283.

Mader, H.J. 1984. Animal habitat isolation by roads and agricultural fields. Biological Conservation **29**:81-96.

Mader, H. J., Schell, C. and Kornacker, P. 1990. Linear barriers to arthropod movements on the landscape. Biological Conservation **54**:209-222.

Maltby, L., Forrow, D. M., Boxall, A. B. A., Calow, P. and Betton, C. I.. 1995. The effects of motorway runoff on freshwater ecosystems. Environmental Toxicology and Chemistry **14**:1079-1092.

Marshall, C., Corner, A. and Tattersfield, P. 1995. An amphibian mitigation scheme for the A34 Wilmslow and Handforth Bypass, Cheshire, United Kingdom. *in* K. Canters, editor. Habitat fragmentation and infrastructure. Proceedings of the international conference on habitat fragmentation, infrastructure and the role of ecological engineering, MECC, Maastricht, 18-21 September 1995. Ministry of Transport, Public Works and Water Management, Delft, the Netherlands.

Mead, C. 1997. A pathetic bundle of feathers. British Wildlife **8**(4): 229-231.

Merriam, G. 1991. Corridors and connectivity: animal population in heterogeneous environments. Pages 133-142 *in* D.A. Saunders and R.J. Hobbs, editors. Nature Conservation 2: the role of corridors. Surrey Beatty & Sons, Chipping Campden.

Morris, P., editor. 1994. The hedgehog. The mammal society, London.

Moshe, I., and Mayer, R. 1998. Spatio-temporal trends in armadillo diurnal activity and road-kills in central Florida. http.www.nal.usda.gov/ttic/tektran/data/000008/60/0000086075.html.:1.

Munguira, M.I., and Thomas, J.A. 1992. Use of road verges by butterfly and burnet populations and the effect of roads on adult dispersal and mortality. Journal of Applied Ecology **29**:316-329.

Muskett, C. J. and Jones, M. P. 1980. The dispersal of lead, cadmium and nickel from motor vehicles and effects on roadside invertebrate macrofauna. Environmental Pollution **23**:231-242.

National Conservancy Council, editor. 1984. Nature conservation in Great Britain. NCC, Peterborough.

Nicholls, A.O., and Margules, C.R. 1991. The design of studies to demonstrate the biological importance of corridors. Pages 49-61 *in* A. Saunders and R.J. Hobbs, editors. Nature conservation 2. The role of corridors. Surrey Beatty and Sons, chipping Norton, New South Wales.

Nieuwenhuizen, W., and van Apeldoorn, R.C., editors. 1995. Project Versnippering. Deel 20A Mammal use of fauna passages on natinal road A1 at Oldenzaal. Ministry of Transport, Public Works and Water Management, Delft, Netherlands.

Oggier, P. 1997. roads as barriers to the dispersal of the endangered land snail *Helicella itala. in* K. Canters, editor. Habitat fragmentation and infrastructure. Proceedings of the international conference on habitat fragmentation, infrastructure and the role of ecological engineering, MECC, Maastricht, 18-21 September 1995. Ministry of Transport, Public Works and Water Management, Delft, the Netherlands.

Opdam, P. 1990. Dispersal in fragmented populations: the key to survival. Pages 3-17 *in* R.G.H. Bunce and D.C. Howard, editors. Species dispersal in agricultural habitats. Belhaven, London.

Oxley, D.J., Fenton, M.B. and Carmody, G.R. 1974. The effect of roads on populations of small mammals. Journal of Ecology **11**: 51-59.

Paquet, P. and Callaghan, C. 1996. Effects of linear developments on winter movements of gray wolves in the Bow River valley of Banff National Park, Alberta. *in* G.L. Evink, P. Garrett, D. Zeigler and J. Berry (editors). Proceedings of the Transportation Related Wildlife Mortality Semina. FL-ER-58-96. Florida Department of Transportation, Tallhassee, Florida.

Parr, T.W., and Way, J.M. 1988. Management of roadside vegetation: the long term effects of cutting. Journal of Applied Ecology **25**:1073-1087.

Pulliam, H.R. 1988. Sources, sinks and population regulation. American Naturalist **132**:652-

661.

Putman, R.J. 1997. Deer and road traffic accidents: options for management. Journal of Environmental Management **51**:43-57.

Reh, W., and Seits, A. 1990. The influence of land use on the genetic structure of population of the common frog *Rana temporaria*. Biological Conservation **54**:239-249.

Reijnen, R., and Foppen, R. 1997. disturbance by traffic of breeding birds: evaluation of the effect and considerations in planning and managing road corridors. Biodiversity and Conservation **6**:567-581.

Reijnen, R., Foppen, R., ter Braak, C. and Thissen, J. 1995. The effects of car traffic on breeding bird populations in woodland. Journal of Applied Ecology **32**:187-202.

Rich, T.C.G. 1994. Wildlife Corridors. In Practice **11**.

Richardson, J.H., Shore, R.F., Treweek, J.R. and Larkin, S.B.C. 1997. Are major roads a barrier to small mammals? Journal of Zoology **243**:840-846.

Rotar, J.T., and Adamic, M. 1995. Wildlife traffic relations in Slovenia. Problems arising with the construction of motorway network and possibilities of their mitigation. *in* K. Canters, editor. Habitat fragmentation and infrastructure. Proceedings of the international conference on habitat fragmentation, infrastructure and the role of ecological engineering, MECC, Maastricht, 18-21 September 1995. Ministry of Transport, Public Works and Water Management, Delft, the

Netherlands.

Salim, M. 1989. Effects of salinity and relative humidity on growth and ionic relations of plants. New Phytologist **113**:13-20.

Sangwine, A. 1990. Roadside Horticulture. Landscape Design **190**:38-40.

Sarkar, R. K., Banerjee, A. and Mukherji, S. 1986. Acceleration of peroxidase and catalase activities in leaves of wild dicotyledonous plants, as an indication of automobile exhaust pollution. Environmental Pollution (Series A) **42**:289-295.

Saunders, D.A., and Hobbs, R.J. 1991. The role of corridors in conservation: what do we know and where do we go? Pages 421-427 *in* D.A. Saunders and R.J. Hobbs, editors. Nature conservation 2: the role of corridors. Surrey Beatty.

Schmidt, W. 1989. Plant dispersal by motor cars. Vegetatio **80**:147-152.

Schonewald- Cox, C. and Buechner, M. 1992. Park protection and public roads. In: Fieldler, P. L. and Jain, S. K. (eds). Conservation Biology – the theory and practice of nature conservation, preservation and management. Chapman and Hall, London.

Scott, N. E. 1985. The updated distribution of maritime species on British roadsides. Watsonia **15**:381-386.

Scott, N. E. and Davidson, A. W. 1982. De-icing salt and the invasion of road verges by maritime plants. Watsonia **14**:41-52.

Scott, N.E., and Davidson, A.W. 1985. The distribution and ecology of coastal species on roadsides. Vegetatio **62**:433-440.

Seabrook, W. A. and Dettmann, E. B. 1996. Roads as activity corridors for cane toads in Australia. Journal of Wildlife Management **60**:363-368.

Simberloff, D., Farr, J.A., Cox, J. and Mehlaman, D.W. 1992. Movement Corridors: Conservation bargains or poor investments? Conservation Biology **6**(4 December):493-504.

Slater, F. 1995. Wildlife Road Casualties. British Wildlife **5**:214-215.

Soule, M.E., editor. 1987. Viable populations for conservation. Cambridge University Press, Cambridge.

Spellerberg, I.F. 1998. Ecological effect of roads and traffic: a literature review. Global ecology and biogeographical letters **7**:317-333.

Spellerberg, I. F. and Gaywood, M. J. 1993. Linear features: linear habitats and wildlife corridors. English Nature Research Report No 60. 30pp. English Nature, Peterborough, UK.

Therivel, R., and Thompson, S. 1996. Strategic environmental assessment and nature conservation. Report to English Nature. English Nature, Peterborough.

Thompson, J. R. and Rutter, A. J. 1986. The salinity of motorway soils. Journal of Applied Ecology **23**:299-315.

Thompson, J. R., Rutter, A. J. and Ridout, P. S. 1986. The salinity of motorway soils 2. Distance from the carriageway and other local sources of variation in salinity. Journal of Applied Ecology **23**:269-280.

Tyser, R. W. and Worley, C. A. 1992. Alien flora in grasslands adjacent to road and trail corridors in Glacier National Park, Montana USA. Conservation Biology **6**:253-262.

van Apeldoorn, R.C. 1995. Fragmented mammals; what does that mean? *in* K. Canters, editor. Habitat fragmentation and infrastructure. Proceedings of the international conference on habitat fragmentation, infrastructure and the role of ecological engineering, MECC, Maastricht, 18-21 September 1995. Ministry of Transport, Public Works and Water Management, Delft, the Netherlands.

van der Zande, A.N., Keurs, W.J. and van der Weijden, W.J. 1980. The impact of roads on the densities of four bird species in an open field habitat - evidence of a long-distance effect. Biological Conservation **18**:299-321.

van der Zee, F.F., Weitz, J., ter Braak, C.J.F., van Apeldoorn, R.C. and Vink, J. 1992. Landscape change as a possible cause of the badger *Meles meles* L. decline in the Netherland. Biological Conservation **61**:17-22.

van Langevelde, F., and Jaarsma, C.F. 1995. Habitat fragmentation, the role of minor rural roads

(MRRs) and their traversability. *in* K. Canters, editor. Habitat fragmentation and infrastructure. Proceedings of the international conference on habitat fragmentation, infrastructure and the role of ecological engineering, MECC, Maastricht, 18-21 September 1995. Ministry of Transport, Public Works and Water Management, Delft, the Netherlands.

Verboom, J., editor. 1995. Project Versnippering 23A. Dispersal of Animals and Infrastructure. A model study: summary. Ministry of Transport, Public Works and Water Management, Delft, Netherlands.

Vermeulen, H.J. 1994. Corridor function of a road verge for dispersal of stenotopic heathland ground beetles *carabidae*. Biological Conservation **69**:339-349.

Volk, F., and Glitzner. 1998. Assessment of barrier effects on red deer due to motorways in Austria. First steps at assessing the permeability of the 1990k fenced motorways. Poster presentation at the 3rd conference, route et faune sauvage. (Strasbourg)

Way, J.M. 1977. Roadside verges and conservation in Britain: a review. Biological Conservation **12**:65-74.

Welch, D. & Welch, S. 1988. Occurrence of *Armeria maritima* (Mill.) Willd. on an inland roadside in north eastern Scotland. Watsonia **17**:96-97.

Table 1. A summary of the ecological impacts of extant roads upon local biota.

ECOLOGICAL IMPACT	EFFECT	SOURCE
POLLUTION:		
Foreign material used in construction.	May cause local pH change.	Detwyler 1971.
Dust.	Affecting photosynthesis, respiration, transpiration and facilitating pollutant impacts.	Farmer 1993.
De-icing salt.	Causes local salination and the spread of maritime species along verges.	Davidson 1971, Foster and Maun 1978, Jones 1981, Salim 1989, Scott 1985, Scott and Davidson 1982, Thompson and Rutter 1986, Thompson et al. 1986, Welch and Welch 1988.
Exhaust output including carbon monoxide, sulphur dioxide, nitrogen oxides, ozone, organic gases (e.g. ethylene) and heavy metals (e.g. lead).	Effects include stunted plant growth, increased heavy metal concentration in biota, and changes in ecological community composition.	Schonewald-Cox and Buechner 1992, Sarkar et al. 1986, Muskett and Jones 1980, Angold 1997b.
CHANGES IN LOCAL HYDROLOGY.:		
Increased runoff from impervious surfaces. Pollutants such as hydrocarbons and heavy metals in surface run-off from the road	Pollutants may enter the stream network and cause changes in the diversity and composition of aquatic macroinvertebrates.	Maltby et al. 1995.
Changes in streamflow.	Culverts can alter water tables in the vicinity, and roadside ditches connected to the stream network cause higher, earlier discharge and greater erosion and sedimentation.	Jones and Grant 1996.
DISTURBANCE EFFECTS:		
Gusts of wind from passing vehicles.	May inhibit plant growth and cause necrosis (yellowing) of leaves near roads.	Fluckiger et al. 1978.
Increased human access and noise.	disturbance cause reductions in bird population densities near roads in the Netherlands.	Reijnen et al. 1995.
PHYSICAL BARRIERS TO THE MOVEMENT OF ANIMAL SPECIES:		
Barrier effect.	Roads act as physical barriers to some species, and hinder the dispersal of others.	Andrews 1990, Baur and Baur 1990, Mader 1984, Mader et al 1990, Reh and Seits 1990.
Fauna mortality.	the amount of wildlife killed on roads is very much greater than was once thought.	Fehlberg 1994.
PROVISION OF ECOLOGICAL HABITAT AND CORRIDORS:		
Provision of linear habitat on the road verge.	The ecological and conservation value of road verges has been demonstrated.	Way 1977.
Provision of ecological corridors along road verges.	There is considerable interest in the theory that road verges act as ecological corridors, but so far little hard evidence to substantiate the theory. Roadsides do however play a prominent role in the establishment and dispersal of the alien flora, and the introduced cane toad in Australia uses roads as activity and dispersal corridors.	Spellerberg and Gaywood 1993, Tyser and Worley 1992, Seabrook and Dettmann 1996.

Table 2. The impact of roads on Sites of Special Scientific Interest (SSSIs). Data for Oxfordshire UK.

Size of SSSI	small (<5ha)	medium (5-50ha)	large (>50ha)	Total
Number (%) of sites	53 (42%)	56 (44%)	18 (14%)	127
Combined area (%) of sites	96 ha (2%)	1160 ha (28%)	2890 ha (70%)	4146 ha
Number (%) of sites with:				
no road	31 (58%)	35 (63%)	6 (33%)	72 (57%)
a road adjacent	19 (36%)	17 (30%)	5 (28%)	41 (32%)
a road through	3 (6%)	4 (7%)	7 (39%)	14 (11%)
% habitat affected by roads through sites (% of combined area) assuming:				
5m road width	10% (1%)	6% (1%)	2% (1%)	2% (1%)
5m road width plus 5m impact zone either side	30% (2%)	17% (2%)	6% (2%)	7% (2%)
5m road width plus 100m impact zone either side	100% (2%)	100% (10%)	80% (28%)	90% (23%)

Table 3. The current extent of research on the different impacts of fragmentation resulting from roads, indicating the level at which the research has been undertaken, the research gap and the level at which research is still required to fill that gap.

Topic	Current Research Level	Research Gaps	Approach/Method
Barriers	individual / species	population / community level	multi-species & probably sub-community approach; long term population studies
Corridors	individual / species	population / community level	multi-species & probably sub-community approach, long term population studies
Mortality	individual / species /community	population	long-term population studies
Habitat	population / community	population / community level	survey, long-term monitoring
Eco-Passages	individual / species	population / community level	multi-species approach, long term population study