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RESEARCH REVIEW

Ecological effects of roads and traffic: a literature review

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Abstract. This survey of the literature on the ecological effects of roads and traffic revealed many articles published over many years in peer reviewed journals. There has also been a growing number of reports on the ecological effects of roads produced by government authorities. Whereas few reports have been published on assessing the ecological impacts, there has been a rapidly growing number of reports on methods for mitigation. Gaps in research include the effects of heavy metal accumulation and the processes and effects resulting from habitat fragmentation. There is a need to assess the effectiveness of underpasses and tunnels and the nature and functioning of buffer zones. A literature database has been assembled and is being updated.

Key words. Roads, highways, motorways, traffic, ecological effects and risks, barrier, pollution.

INTRODUCTION

In the U.S.A., U.K., the Netherlands, Australia and New Zealand, there has been growing concern about the ecological effects (or ecological risks) of roads and traffic. The general ecological effects of roads and traffic on biota are summarized in Table 1. (The terms biota and wildlife are both used; for the purposes of this paper these terms have similar meanings except that wildlife would exclude domesticated plants and animals.) Prompted by the apparent increase in publications in this area, the New Zealand Department of Conservation (DoC) awarded a contract to the author for a survey of the literature (contract No. 2165). The main objectives were to survey the literature on the ecological effects of roads and traffic on the natural environment, habitats and species in protected areas and to identify the literature dealing with environmental assessment and ways of mitigating impacts from roads and traffic (Spellerberg & Morrison, 1998).

This paper is extracted from the DoC report. The main aim here is to provide examples of the range of literature and extent of work on various topics dealing with the effects of roads on organisms, habitats and landscapes. Examples of literature on the assessment of risks and impacts, as well as mitigation, are also included. The references cited in this paper are now included in a literature database maintained by the author. There are currently 388 references in this database.

METHODS AND MATERIALS

The work concentrated mostly on reports of original investigations rather than reviews (apart from the following: Leedy (1978), Watkins (1981), Gilbert (1989), Andrews (1990), Aanen *et al.* (1991), Bennett (1991), Atkinson & Cairns (1992), Schonewald-Cox & Buechner (1992), Ramsay (1994), Edmunds (1995), Forman (1995), Noss (1995), Southerland (1995), and Environmental Resources Management (1996)). The conclusions in this paper are generalizations based on the author's interpretation of those original reports. This literature report deals mainly with literature in English. Most of the references were found by searching journals and databases such as OPAC, INNZ—New Zealand, SSCI, CAB Abstracts, Current Contents, New Zealand Science and Technology, Agricola and Spectrum. A home page was put on the Worldwide Web and advertisements were placed in journals and bulletins (The New Zealand Ecological Society Newsletter, The British Ecological Society Bulletin, The Biologist, Journal of Institute of Biology).

Table 1. A summary of ecological effects of roads.

Effects during construction

There is a direct loss of habitat and biota.
There are effects resulting from the infrastructure and supporting activities for construction.
The impacts may occur beyond the immediate vicinity of the road; for example changes in the hydrology. Mining for aggregates for the road may take place in a different area. It is important therefore to agree on the geographical boundary for an impact assessment.

Short term effects (of a new road)

The new linear surface creates a new microclimate and a change in other physical conditions extends varying distances from the road edge.
The newly created edge provides habitat for edge species.
Plant mortality increases along the edge; and such mortalities may extend from the road edge for varying distances.
The mortality of plants has direct and secondary effects on other organisms.
Some fauna will move from the area of the road as a result of habitat loss and physical disturbance.
Animals are killed by traffic.

Long term effects

Animals continue to be killed by traffic.
The road kills have secondary effects as carrion.
The loss of habitat and change in habitat extends beyond the edge of the road.
The changes in the biological communities may extend for varying distances from the road edge.
There is fragmentation of habitat and this in turn has implications for habitat damage and loss, for dispersal and vagility of organisms, and for isolation of populations.
The edge habitat (or ecotone) and traffic on the road may facilitate dispersal for some taxa, including pest species.
The dispersal of pest species via ecotones or traffic may have secondary effects on biological communities.
Associated structures such as bridges and tunnels may provide habitats for some taxa.
The run-off from the roads affects aquatic communities.
Emissions, litter, noise and other physical disturbances may extend into the roadside vegetation for varying distances and result in changes in species composition.

The survey revealed some literature databases and overviews, notably from the U.S.A., the U.K. and the Netherlands. These databases are in both electronic form and printed form and are continuously being updated (they are not publications).

Literature databases

(i) Transportation Research Board Publications U.S.A.

This is a bibliography with abstracts on the ecological and environmental effects of highways (kindly provided by Barbara Post, TRB Library, U.S.A.).

(ii) ROAD-RIP Roads Bibliographic database

This has been compiled by the Wildlands Centre for Preventing Roads (CPR). Based in the U.S.A., it includes many hundreds of citations (kindly provided by Bethanie Walder at Wildlands CPR, P.O. Box 7516, Missoula, MT 59807, U.S.A.).

Some of the ROAD-RIP database citations were State orientated and many were pollution orientated. Examples include the following (numbers in brackets were the number of citations under that heading): Indiana (12), Illinois (33), Mid-west (4), Ohio (21), storm run-off (94), changing hydrology (16), glacial streams (8), bank erosion (19), toxins (97), emissions (55), ground (10), hydrocarbons (33), lead (134), air (180), water (131), metals (13), noise (19), urban (85), and pollution control (178).

Reviews and reports

Reviews on the ecology of roads and traffic include the following: Leedy (1978), Watkins (1981), Gilbert (1989), Andrews (1990), Bennett (1991), Atkinson & Cairns (1992), Schonewald-Cox & Buechner (1992), Ramsay (1994), Forman (1995), Noss (1995) and Southerland (1995).

Reports (not necessarily with bibliographies) with reviews about the effects of roads on nature (some with information on mitigation) have been published in several countries. In the Netherlands, in particular, there are Government sponsored promotional publications about ecological effects of roads and also well publicised methods for attempting to deal with habitat fragmentation. Not all reviews seemed to be objective. Some considered that roads are 'bad' and proceeded to review the literature in that light.

The following are examples of reports.

(i) *Nature engineering and civil engineering works.* Pudoc, Wageningen (Aanen *et al.*, 1991). This is a collection of papers on the relation between nature and civil engineering works, including many examples of mitigation methods.

(ii) *Head on Collision 1995: The Wildlife and Roads Report* (Edmunds 1995). In this report prepared by Janet Edmunds for the Cheshire, Cumbria and Lancashire Wildlife Trusts, the threats to important wildlife sites from road developments in the U.K. were reviewed. The road developments mentioned in the report were in Cumbria, Lancashire, Merseyside, Greater Manchester and Cheshire.

(iii) *The significance of secondary effects from roads and road transport on nature conservation* (Environmental Resources Management, 1996). This was published as the English Nature Research Report No. 178 (English Nature, Peterborough). This report presented the findings of a research contract. The information was obtained from a variety of sources including the following: organizations with interests in nature conservation and roads; literature searches through the British Library; and representatives of English Nature. The report included a particularly comprehensive list of references (about 210).

RESULTS AND DISCUSSION

Topics considered only briefly

The review of the literature was comprehensive but not all topics have been included in this paper for reasons of brevity. The following topics are considered only briefly.

(i) Environmental costs of roads

There is a growing interest in the environmental costs of roads; see for example Maddison *et al.* (1996).

(ii) Ecological effects of secondary activities

Literature on the ecological effects arising from secondary activities such as the mining of aggregates for road building, transportation of materials for road maintenance and the use of fossil fuels for transportation has not been included.

(iii) Interactions between biota and roads

Whereas this paper considers the literature on ecological effects of roads on biota and ecosystems, there are effects of nature on roads, traffic and products of traffic. For example, trees may prevent land slips on to roads (Haigh *et al.*, 1995). Trees and other plant life forms accumulate heavy metals (Ward, Brooks & Reeves, 1974) and may help to reduce the amount of airborne pollutants, especially in urban areas (Dochinger, 1980; Greszta, 1982).

(iv) Impacts of traffic and tourism in new areas facilitated by new roads

The environmental impacts arising from developments in tourism may have ecological implications. Similarly, there may be ecological effects arising from the impacts of off-road vehicles. Examples of the literature on these topics include Belsky (1987), Kearsley (1990) and Forbes (1992).

(v) Effects of roads on the physical environment

There are many reports about the effects of roads on the physical environment. The effects on geology, water run-off, pollution and sediment load in streams have been well documented e.g. Watkins (1981), Ball, Jenks & Aubourg (1998).

(vi) Structures associated with roads

There are many developments and structural elements associated with roads, e.g. rest areas, signs, electricity poles and wires, fences, retaining walls, contiguous piles, bridges, viaducts and tunnels. The implications of these developments and structures for wildlife and their use by plants and animals is not discussed here.

(vii) De-icing agents

Many surveys and much experimental work has been undertaken on the effects of de-icing agents since at least the 1960s (e.g. Westing, 1969; Davison, 1971).

(viii) Geological conservation

Concern about the effects of roads on the natural environment include the implications for geological conservation. For example, Larwood & Markham (1995) discuss the best practical and technical solutions available for geological and geomorphological conservation in relation to road construction.

Main topics considered

In the review of topics that follows, it is recognized that not all topics are confined to the effects of roads. For example, powerline swathes may constitute wildlife habitats or barriers; lighting is not confined to roads; and habitat fragmentation is caused by many kinds of developments.

Pollution and disturbance effects on biota and ecosystems

Pollutants impacting on biota include noise, light, sand, dust and other particulates, metals such as Pb, Cd, Ni and Zn, and gases such as CO and NO_x. There is a wide range of pollutants in water run-off from roads (see Gjessing *et al.* (1984) for a good overview) and this range seems to have resulted in less than comprehensive studies for some specific pollutants. The extent to which emissions and disturbances extend from a road have been researched by some authors (see Schonewald-Cox & Buechner (1992) for a review). For example, above normal traces of heavy metals have been recorded in plants up to 150 m from roads.

There are both secondary effects and synergistic effects, some of which may be complex in their operation. For example, road pollutants may cause physiological stress in some plants and make them more susceptible to pest attack, as has been shown by work on aphid infestations of roadside trees in Switzerland (Braun & Fluckiger, 1984).

In one review of toxic substances in flowing water, Hellawell (1988) described the wide range of potential pollutants and noted that very few generalizations can be made about their effects on biota. Different species of plants and animals tend to respond to different pollutants in different ways, and even different stages in the life history may have very different responses.

(i) Noise and artificial lighting

Noise and artificial lighting have been shown to affect some wildlife. For example Reijnen, Veenbass & Baker (1995a), and Reijnen *et al.* (1995b) have researched the effects of car traffic on breeding bird populations in the Netherlands. They found reductions in bird population densities and argued that noise load is probably the most important cause of the reduced densities. Reijnen & Foppen (1994) reported that male willow warblers *Phylloscopus trochilus* close to highways experienced difficulties in attracting or keeping a mate. It was suggested that the distortion of the song by traffic noise might be a possible cause.

The effects of road lighting and traffic light on species of animals and plants has attracted much attention and has been reviewed in a few reports e.g. Environmental Resources Management (1996). The effects are wide ranging, e.g. for some bird species, artificial road lighting may contribute to extended feeding times (Hill, 1992), and for some crop plants road sodium vapour lamps may affect their growth (Sinnadurai, 1981).

(ii) Dust and sand

There appear to be few studies of the chemical and physical effects of road dust on nature; some of these relate to specific regions or biomes such as the Tundra and Taiga (see for example the work of Forbes (1995) in Siberia and also the review by Walker & Everett (1987) of impacts in arctic regions). Physical effects on plants may include cell destruction and blocked stomata. A review by Farmer (1993) on the effects of dust on plants and plant communities includes literature on the effects of different dust types on crops, grasslands, heathlands, trees, arctic bryophyte and lichen communities. Dust may affect photosynthesis, respiration and transpiration, and facilitate effects of gaseous pollutants. Farmer found that epiphytic lichens, sphagnum and other mosses were the most sensitive of those taxa studied.

(iii) Heavy metals (trace metals)

Land-use can influence the types and levels of trace metals in road dust. For example, Wong, Cheung & Wong (1984) studied the effects of roadside dust on seed germination and root growth in vegetable crops in China. They found enhanced root growth for plant material collected from areas where there was low traffic density. For plant material collected from a high traffic density site there was marked reduction of root growth. Amongst invertebrates, the effects may or may not be detrimental. For example, Przybylski (1979) working in agricultural and horticultural areas of Poland found that whereas combustion gases (containing lead compounds) may reduce species richness in some arthropod groups, other groups such as members of the Family Aphididae and some Heteroptera flourished. Muskett & Jones (1980) working by roads in west London measured heavy metal concentrations and found that their data did not reveal an obvious decline in either numbers of terrestrial invertebrate macrofauna (caught in pitfall traps at various distances from the road) or in species diversity ('alpha' species diversity index) with increasing metal pollution load.

Some reports draw attention to the limited research on the effects of animals feeding on biota near roads. There has been concern about bio-accumulation of metals from one trophic level to another (e.g. Scanlon (1987), working in Virginia, U.S.A.). There have also been warnings about possible effects on humans who may consume roadside plants and fruits (e.g. see the report from Rodriguez-Flores & Rodriguez-Castellón (1982) on roads in Puerto Rico).

(iv) Gases

The direct effects of road traffic gases (SO_2, CO_2, CO, NO_x and Hydrocarbons) on biota other than humans have been researched. Effects on plant growth have been observed; e.g. Sarkar, Banerjee & Mukherji (1986) recorded stunted growth in plants near highways in Calcutta. Kammerbauer *et al.* (1986) noted a lack of experimental work on the effects of exhaust emissions on forest trees (noting much controversy about reasons for die-back in forest trees near roads). They found evidence for injuries of Norway Spruce by CO and NO_x). They also reported reductions in these effects when catalytic converters are used. In the north of England, Spencer & Port (1988) found that *Lolium perenne* L. grows more vigorously in soil taken from near roads and that NO_x and de-icing salt are possible causes. In Angold's (1997) detailed study of the ecological effects of road pollutants on heathland communities in southern England, it was found that nitrogen (nitrogen oxides from traffic) caused increase growth in plant species (effects were measured up to 200 m into the heathland) and consequently the species composition changed.

(v) Effects on aquatic systems and biota

Effects of roads and run-off on aquatic biota and aquatic ecosystems have attracted much attention. The role of wetlands as sinks for metals and macronutrients from roads has also been much researched (e.g. Yousef, Baker & Hvitved-Jacobsen, 1996). This is an area of possible conflict; on one hand there are attempts to avoid pollution of wetlands and on the other hand there are wetlands being used as pollution sinks.

A particularly detailed study on the effects of motorway run-off on freshwater ecosystems has been undertaken by Maltby *et al.* (1995). They researched seven streams receiving drainage from the M1 Motorway in England and reported effects on species diversity and in species composition of macro-invertebrate assemblages but found no changes on either diversity or abundance of epilithic algae.

Other effects of roads on biota and habitats

Examples of reports on the effects of roads and traffic are given in Table 2. Southerland (1995) has noted the incremental effects of road developments and argued that roads result in loss of biological diversity. The effects of roads on biota and habitats are often described as being either negative or positive. For example, road kills are seen as negative and an increase in edge habitat is seen as positive. Although an increase in edge habitat is sometimes claimed as being positive, the effects on the wider biotic community may not have been researched. This dichotomy is simplistic because it does not analyse the effects in the wider context of community ecology. For example, although there are many reports in the literature on road kills, the longer term effects on the population dynamics of the species concerned may not have been researched. In general, road kills do not seem to have detrimental effects on animal populations except in those cases of species with small or diminishing populations. Bennett (1991) has written a review on wildlife road mortality.

The secondary effect on other species seems not well researched. One example of a secondary effect was the transportation of fungal spores along roads which may have facilitated the spread of a pathogenic fungus in forests in southern Australia (Weste, 1977).

(i) Habitat fragmentation by roads

Habitat fragmentation (sometimes referred to as landscape fragmentation) has become a major focus of research in conservation biology. This is because it is believed by many to have by far the greatest detrimental impact of all impacts on nature (e.g. Wilcox & Murphy (1985), Usher (1987), and Robinson & Quinn (1992), Abensperg-Traun *et al.* (1996), Marsh & Pearman (1997)). Andrews (1990) has written an extensive review about roads and habitat fragmentation. An extensive

Table 2. Examples of the literature reporting effects of roads and traffic on wildlife (the categories are not mutually exclusive).

Loss of habitat and changes in biotic communities

Angold (1997) Impacts of roads on adjacent heathlands.
Reijnen & Foppen (1994) Birds, *Phylloscopus trochilus* (L.), Netherlands.
Sherburne (1985) Effects on several species of birds and mammals, Northern Maine, U.S.A.

Linear habitats

Adams & Geis (1983) Small mammals, U.S.A.
Reijnen & Foppen (1994) Birds, Netherlands.
Warner (1992) Effects on birds, Illinois.
Lamont *et al.* (1994) Effects on the plant, *Banksia hookeriana* Meissner, Australia.
Munguira & Thomas (1992) Butterflies, U.K.

Affecting behaviour (including dispersal) of mammals

Adams & Geis (1983) Small mammals, U.S.A.
Bakowski & Kozakiewicz (1988) Small mammals, Poland.
Brody & Pelton (1989) Bears, North Carolina.
Burnett (1992) Small mammals, Australia.
Garland & Bradley (1984) Desert rodents, Mojave Desert, Nevada.
Korn (1991) Small mammals, Germany.
Mader (1984) Wood mice, Germany.
Merriam *et al.* (1989) Mice, Ottawa.
Murphy & Curatolo (1987) Caribou, Canada.
Murphy & Dowding (1994) Stoats, New Zealand beech forest.
Oxley, Fenton & Carmody (1974) Small mammals, Canada.

Affecting birds

Canaday (1996) Several species, Ecuador.
Clark & Karr (1979) Several species, Illinois.
Ferris (1979) Several species, Maine, U.S.A.
Johnson (1990) Bald eagles, Southern Alaska.
Reijnen *et al.* (1995a, b) Several species, Netherlands.
Zande *et al.* (1980) Several species, Netherlands and re-analysis of a previous study.

Affecting biota other than birds and mammals

Baur & Baur (1990) Snails (*Arianta* spp.), Canada.
Mader (1984) Carabid beetles, Germany.
Mader *et al.* (1990) Arthropods, Germany.
Majer & Beeston (1996) Alpha diversity of ants and comparison of effects of roads with effects of other land uses in Western Australia.
Vos & Chardon (1998) Moor frogs (*Rana arvalis* Nilsson), Netherlands.

Mortalities

Adams & Geis (1983) Small mammals, U.S.A.
Bennett (1991) Good review for all taxa.
Bernardino & Dalrymple (1992) Snakes, Florida.
Case (1978) Various animal taxa, Nebraska.
Dhindsa *et al.* (1988) Birds, India.
Dowler & Swanson (1982) Cedar waxwings (*Bombycilla cedrorum* Vieillot) Texas.
Fahrig *et al.* (1995) Amphibians, Ottawa, Canada.
Illner (1992a) Grey partridge (*Perdix perdix* L.), Germany.
Illner (1992b) Owls, Germany.
Madsen (1996) Otters (*Lutra lutra* L.), Denmark.
Morris & Morris (1988) Hedgehogs, New Zealand.
Romin & Bissonette (1996) Deer, U.S.A.
Vestjens (1973) Various taxa, New South Wales.

summary of some major effects of landscape fragmentation on sensitive species or systems, particularly as determined by roads within parks, has been provided by Schonewald-Cox & Buechner (1992).

The implications for conservation arising from habitat fragmentation have resulted in many hundreds of papers about the supposed importance of island biogeography to nature reserve design. The usefulness of island biogeographical studies to nature conservation on mainlands is questionable (Spellerberg, 1991). There are many ways of quantifying habitat fragmentation, e.g. in addition to calculations of the rate of reduction of total habitat area and increase in the number of fragments, some studies on habitat fragmentation have measured the extent of isolation of habitats, area of edge (and edge related indices), shape of fragments, and degree of spatial heterogeneity. The research on forest edges has also prompted discussion about methods of analysis, e.g. Salisbury (1996).

(ii) Edge effects and microclimates in forests

In a study in the Rocky Mountains, Reed, Johnson-Barnard & Baker (1996) assessed the extent of forest fragmentation caused by roads and by clearcut forestry. They found that roads did contribute to forest fragmentation and that roads contributed more to fragmentation than did clearcuts. Furthermore, the edge habitat created by roads was 1.54–1.98 times the extent of edge habitat created by clearcuts.

In a study of woodlands in Ohio, Kupfer (1996) looked at patterns and determinants of edge vegetation and concluded that microclimate influences edge succession. Williams-Linera (1990) working on forest edges in tropical pre-montane wet forests of Panama found changes in microclimate penetrating 15 m into the forests. Young & Mitchell (1994) researched the microclimate and vegetation edge effects of forest margins created 100–130 years ago. Their research was in fragmented podocarp-broadleaf forest in the North Island of New Zealand. Penetration of microclimatic edge effects was approximately 50 m, regardless of forest size. They suggested that microclimatic edge effects on processes such as germination and early establishment are a major feature of forest dynamics.

(iii) Effects of fragmentation on forest birds

Rich, Dobkin & Niles (1994) considered that extensive fragmentation of what was formerly contiguous forest in eastern North America is a primary cause of decline in forest bird species. In their own study, they reported that even narrow forest-dividing corridors affect the distribution and abundance of birds.

(iv) Effects on small mammals

In Kansas, small road clearances less than 3 m wide were shown to affect small mammals such as voles and rats (Swihart & Slade, 1984). In Australia, Mansergh & Scotts (1989) showed that the social organization and survival rates of the mountain pigmy-possum (*Burramys parvus* Broom) are disrupted because the habitat has become fragmented by roads (and other developments within a ski resort).

(v) Consequences for feral predators

Fragmentation of habitats may have implications for dispersal of feral predators but little research seems to have been done in this area (May & Norton, 1996).

(vi) Roads, fragmentation and invasive plant species

As well as contributing to habitat fragmentation, roads and road traffic facilitate the dispersal of plant species. There has been concern expressed about the spread of alien and invasive species, particularly with regard to invasions of nature reserves. For example, Brothers & Spingarn (1992) working in Central Indiana, U.S.A., drew attention to the possibility of forest fragmentation encouraging alien invasions for at least two reasons. First, fragmentation increases the ratio of non-forest to forest and of forest edge to interior habitats. Second, environmental changes at forest edges may provide points of entry for alien species. In New Zealand, Timmins & Williams (1990) have noted that among the important factors influencing the number of problem weeds in reserves are distance from roads and railway lines.

(vii) Roads and roadside verges as linear habitats and wildlife corridors

The total area of roadside verges in some countries has been carefully documented and much has been made of the fact that roads may benefit nature. Birds may feed on the grit on roads, power lines provide perches for birds and roadside verges may provide habitats for some plant and animal species.

In some countries, there is much interest in roadside verges as linear habitats. In Illinois, for example, Warner (1985) studied the movements of free-ranging domestic cats and found that they made disproportionately high use of farmsteads, roadsides and field boundaries. In Indiana, U.S.A., Roach & Kirkpatrick (1985) reviewed the wildlife use of roadside woody plantings and recommended planting regimes. Also in America, Smith (1993) reviewed what are called 'Greenways' and gave an overview of 'greenway ecology' and habitat management. In the U.K., there has been considerable interest in the contribution of roadside verges to conservation (as reviewed by Way, 1977). A detailed analysis of Cheshire's roadside verges has been undertaken (Cheshire Ecological Services, 1995). That report details survey methods, analyses roadside verge habitats and makes recommendations for management and monitoring. Examples of the literature on roadside verges are given in Table 3.

There has been a growing interest in the possible corridor function of roadside verges and the term wildlife corridor is widely mis-used. Whereas many linear landscape features such as roadside verges may provide linear habitats, there is only a small amount of evidence to show that roadside verges are used by animals as conduits for dispersal (Spellerberg & Gaywood, 1993). However, there is now a rapidly growing interest in this topic, especially in Australia (Saunders & Hobbs, 1991; Saunders, Hobbs & Ehrlich 1993).

(viii) Traffic and dispersal of plant species

Dispersal of plant species via road traffic has been addressed in some surveys and an excellent analysis of the mechanism is given in Wace (1977). Dispersal of potential weeds and alien flora via traffic (and by vehicles and humans during road construction) has received attention in the U.S.A., Australia and New Zealand. Timmins & Williams (1990) looked at the accidental spread of weeds through reserves and have noted that reduction in roads could address this problem. The role of roads and traffic in the spread of weeds in Australia has been addressed by Amor & Stevens (1975), Cowie & Werner (1993) and Lonsdale & Lane (1994). Rather than trying to attempt to prevent this form of seed movement via tourist traffic, it was suggested by Lonsdale & Lane (1994) that resources are best spent on detecting and eradicating weed infestations. The conclusion is based on the acceptance that the road has been built and is operational.

The ecology of dispersal of alien species and the ecology of invasions has become a huge research area. In Britain, Usher's (1988) review on biological invasions noted that tourism poses dangers for reserves since there is a positive correlation between visitation rate and the number of introduced species (Macdonald & Frame, 1988; Macdonald *et al.*, 1989).

Assessing the risks and the impacts

There are many examples of Environmental Impact Assessment (EIAs) which deal with road projects in different environments. International organizations such as the IUCN (IUCN, 1996) have outlined the assessment of environmental impacts of new roads. The theory of EIA with regards to roads has been explored in FAO (1989). In the U.K., Hodgen & Ford (1985) described the planning and design of roads for Areas of Outstanding Natural Beauty (AONB). For the State of Washington, Horner & Mar (1983) gave a protocol for assessing the impacts of road operations on aquatic ecosystems. The protocol offers opportunities to forecast potential aquatic impacts at an early stage of development. In the U.K., the Department of Transport (U.K.) (1992) has published a review on 'Assessing the environmental impact of road schemes' which includes effects on wildlife.

In the U.S.A., the National Environmental Policy Act (NEPA) provides a framework for environmental impact assessments and a basis for assessing the effects of road projects. A recent example of an environmental impact assessment of a proposed road and one which addresses many forms of wildlife is the Environmental Impact Statement for the Beaver Basin Rim Road (U.S. Department of the Interior, 1996). The US Department of Transportation has reviewed impact assessments and mitigation with respect to highways and ecology (Erickson, Camagis & Robbins, 1978). Atkinson & Cairns (1992) have also reviewed the ecological risks of highways in the U.S.A. These reports are two of a few which draw attention to the growing risks associated with the transport of hazardous materials.

Some EIA methodology is designed to help identify primary, secondary and tertiary impacts of roads, e.g. Lelièvre & Seródes (1995) have suggested a cause-effect network with three components to assist in identifying secondary and tertiary impacts. The three components are: actions undertaken, environmental characteristics and the stages of the project.

Ecological considerations have been included within EIAs for some roads. For example, Box & Forbes

Table 3. Examples of literature about roads and roadside verges (as linear habitats) and roads as wildlife corridors (facilitating dispersal) for wildlife.

Road verge as habitat

Adams (1984) Small mammals, North Carolina, U.S.A.
Cowie & Werner (1993) Alien plant species, northern Australia.
Hansen & Jensen (1972) Plant communities, Denmark.
Havlin (1987) Birds, Czech Republic.
Lane (1976) Plants, Australia.
Michael (1986) Songbirds, West Virginia, U.S.A.
Munguira & Thomas (1992) Butterflies, U.K.
Newbey & Newbey (1987) Birds, Western Australia.
Reznicek (1980) Halophytes, Michigan, U.S.A.
Roach & Kirkpatrick (1985) Wildlife, Indiana, U.S.A.
Samways (1989) Bush crickets, Southern France.
Tyser & Worley (1992) Alien flora, Montana, U.S.A.
Wester & Juvik (1983) Plant communities, Hawaii.
Wells *et al.* (1996) Reptiles, U.K.
Wilson *et al.* (1992) Plant communities, New Zealand.

Road verge management

Laursen (1981) Mowing frequency and birds, Denmark.
Munguira & Thomas (1992) Butterflies, U.K.
Parr & Way (1988) Long-term effects of mowing, U.K.
Pedevillano & Wright (1987) Visitor management and mountain goats, Montana, U.S.A.
Roach & Kirkpatrick (1985) Wildlife, Indiana, U.S.A.
Sangwine (1992) Landscape planting, U.K.
Thompson, Rutter & Ridout (1986) British native plants tolerant of salinity (U.K.)
Watson, Rice & Monnig (1989) Herbicide (Picloram) for weed control, northern Rockies, U.S.A.

Dispersal studies (via traffic and along and from road verges)

Amor & Stevens (1975) Weeds into forest, Dartmouth, Australia.
Clifford (1959) Seed dispersal via traffic, Nigeria.
Getz, Cole & Gates (1978) Small mammals, Illinois, U.S.A.
Lonsdale & Lane (1994) Weed seeds, northern Australia.
Schmidt (1989) Plant dispersal by traffic, Germany.
Seabrook & Dettmann (1996) Cane toads, N.S.W, Australia.
Timmins & Williams (1990) Weeds in New Zealand forest reserves.
Travis & Tilsworth (1986) Fish in culverts, Alaska.
Vermeulen (1994) Ground beetles, Netherlands.
Wace (1977) Plant species via cars, Canberra, Australia.
Warner (1985) Free range domestic cats, Illinois, U.S.A.
Wilcox (1989) Purple loosetrife (*Lythrum salicaria* L.), New York State, U.S.A.

(1992) suggested a conceptual framework for an ecological input into road projects. However, ecological impact assessment seem far less well researched than other aspects of EIAs. The Institute of Environmental Assessment (IEA, 1995) has produced '*Guidelines for baseline ecological assessment*'. In a recent book edited by Schmitt & Osenberg (1996), there are many ideas for detecting ecological impacts in coastal habitats. In other publications (Reijnen *et al.*, 1995a, b), there are methods for predicting the effects of motorway traffic on breeding bird populations. Reijnen *et al.* (1995a) is a particularly extensive book from the Netherlands and one in which there is very detailed theory and clear practical applications. Environmental monitoring and ecological monitoring should follow on from EIAs or at least be established as part of the EIA process. However, there seems to be a lack of reports dealing with post-EIA environmental monitoring and especially with ecological monitoring.

Redressing the detrimental ecological effects

The need to redress ecological effects of roads is clearly expressed in some general reviews of mitigation and enhancement (e.g. Thrasher, 1983). These general reviews may have helped to influence the World Bank and some governments which previously have supported large road projects. For example, in 1981, the World Bank together with the Brazilian Government jointly funded the $1.5 billion development in southern Brazil with a centrepiece of a 1500 km sealed highway. This highway has been at the centre of a campaign to reform international financial support for such projects (Reid & Bowles, 1997). Some years on the World Bank has published a manual in which the 'negative' environmental impacts of roads and traffic are addressed (World Bank, in press). In the U.S.A., Baker (1998) reports that decades of road construction in the national forests may soon be at an end as a result of the U.S. Forest Service's roads programme. A one year moratorium on new roads in pristine areas, with the exception of some localities in Alaska and the Pacific Northwest, has been proposed. In the U.K., a design manual for roads and bridges has been published in which there are extensive sections on mitigation (Department of Transport, 1993). Work from the Netherlands and from Denmark includes development of policy (Bohemen, 1995) and advice for the wider community with respect to dealing with effects of roads on wildlife. Some of these publications include detailed methods for addressing the ecological effects of roads (e.g. Bekker *et al.*, 1995). The concept of ecological compensation is now Dutch Governmental policy (Cuperus, Canters & Piepers, 1996). In Australia, the Queensland Department of Main Roads (1997) has produced a comprehensive manual about the design, construction, and management of roads in the wet tropics. The mission statement for this manual includes the following: '*To provide safe, equitable and economic roads within the wet tropic region whilst presenting, conserving and rehabilitating the unique natural and cultural values to the greatest extent practical*'. In New Zealand, the organization Transfund New Zealand (1997) has produced a manual for cost benefit analysis of road projects, including ecological features and some information on mitigation.

The literature dealing with ways of redressing environmental and ecological effects includes many topics (Table 4), although it goes without saying that not all are exclusive to roads and traffic. Some authors support an ecosystem approach to redressing the effects of roads, e.g. Southerland (1995) advocated that an ecosystem approach is critical to assessing biodiversity effects (at appropriate scales) and that mitigation of the loss of biodiversity should extend to the provision of adequate buffer areas and habitat corridors.

Reports about means of mitigating the effects of pollution seem to be directed mainly at contamination of wetlands (e.g. Kober & Kehler, 1987) and problems of containing surface run-off from roads. By way of contrast, there has been research on the use of wetlands as a sink for urban water run-off (e.g. Reuter, Djohan & Goldman, 1992).

There is much literature on tunnels and overpasses; mainly on how to construct them. There seems little on monitoring the effectiveness (in terms of use) and effects (in terms of population size, fragmentation of populations and gene flow) of these attempts to reduce barrier effects.

Mitigation banking is not new (see Table 4) but is becoming increasingly popular. It involves compensation for loss or damage to habitats by establishment of wildlife habitats elsewhere (or enhancement of habitats). There is much room for research here, particularly with regard to the ecological restoration techniques.

Landscaping and planting roadside verges to reduce erosion and to provide habitats for wildlife has been widely researched (Table 3). The concept of buffer zones (undisturbed areas or strips) and filter strips (undisturbed except to provide access) has long been popular in conservation and has been researched with respect to roads (Clinnick, 1985). In the U.S.A., agencies such as Wallace, McHarg, Roberts and Todd (WMRT) have produced structured guidelines for buffer zones and corridors (Smith, 1993). The use of buffer zones to minimize effects of herbicide spray drift has been researched by Marrs *et al.* (1992). The use of buffer strips to absorb pollutants has been discussed by Angold (1997). Her research suggests that some dense vegetation may act as sinks for some pollutants.

The best width for a buffer zone has not been well researched except in connection with the prevention of sedimentation of streams. Very little research appears to have been undertaken on how to identify the optimum widths of buffer strips alongside roads. One way of approaching this is to research the nature and extent of the impacts from roads and traffic on wildlife communities. (e.g. Angold, 1997).

Areas for research

(i) Pollution

Whereas there is much research showing rates and levels of accumulation of metals in roadside biota, the

Table 4. Redressing the ecological effects of roads.

Reducing road mortality and barrier effects of roads, bridges, and railway lines
- Evink (1990) Safe crossings for panthers, Florida, U.S.A.
- Feldhamer *et al.* (1986) Roadside fencing and deer, Pennsylvania, U.S.A.
- Hunt *et al.* (1987) Tunnels for mammals, New South Wales.
- Langton (ed.) (1989) Tunnels for amphibians, European.
- Madsen (1993) Faunal passages and road systems, Denmark.
- Mansergh & Scotts (1989) Tunnels for pygmy-possums, *Burramys parvus*, Australia.
- Murphy & Curatolo (1987) Behaviour of caribou where roads run near pipelines, Alaska.
- Nieuwenhuizen & Apeldoorn (1995) Mammal use of underpasses, Netherlands.
- Owens & James (1991) Pelicans and bridges, Texas, U.S.A.
- Reed (1981) Deer and underpasses, Colorado, U.S.A.
- Romin & Bissonette (1996) Deer fences, tunnels and speed controls, U.S.A.
- Salvig (1991) Faunal passages and roads, Denmark.
- Singer, Langlitz & Samuelson (1985) Underpasses for mountain goats, Montana, U.S.A.
- Verboom (1995) Analytical methods for risks of fauna crossing roads, Netherlands.
- Ward (1982) Fencing and deer, Wyoming, U.S.A.
- Yanes, Velasco & Suarez (1995) Vertebrate movement in culverts, Spain.

Mitigation banking
- Howarth (1991) Wetlands, North Carolina, U.S.A.
- Lister (1992) Salmon habitat, British Columbia.

Buffer zones and filters
- Angold (1997) Buffer zones and oligotrophic communities, U.K.
- Clinnick (1985) Buffers for protection of streams from sediment, Australia.
- Swift (1986) Filter strips to prevent sedimentation of streams, Appalachian Mountains, U.S.A.
- Trimble & Sartz (1957) Logging roads, sediments and streams, U.S.A.

effects seem not well researched. As early as 1976, Smith reviewed lead contamination of roadside ecosystems and at that time noted that our understanding of the effects on biota is deficient. More recent reports of the late 1980s continue to mention that we know little about the chemistry of heavy metal uptake in biota. The long-term cumulative effects seem poorly researched. Furthermore there has previously been some controversy with regard to the effects of heavy metal accumulation on roadside forest trees (Backhaus & Backhaus, 1987).

(ii) Long-term effects

There is very little research on long-term ecological effects of roads and how to monitor those effects. This could be particularly relevant to the ecology of invasive species and dispersal of those species via roads and road traffic.

(iii) EIAs

There are many Environmental Impact Assessments of road projects but the level and content of the biological material and also the quality of the ecological content is varied; many reports leave much to be desired. There could be more research on the assessment of ecological impacts of road projects. I recommend an appraisal of the biology and the ecology of EIAs which have been completed for road projects.

(iv) Habitat fragmentation

Many authors consider that fragmentation of habitats by roads may be the most important of the ecological effects of roads and their traffic. Ecological studies of fragmentation are growing in number but there are still very few reports which analyse the effects of fragmentation by roads. There is room for research on analytical techniques as well as on modelling the likely effects.

(v) Methods to reduce barrier effects

Much has been said about the use of wildlife tunnels but there seems to have been little research on their effectiveness e.g. Hunt, Dickens & Whelan (1987), Langton (1989) and Nieuwenhuizen & Apeldoorn (1995).

(vi) Mitigation banking

This is an area in which little research has been done.

(vii) Buffer zones

The concept of buffer zones is widely used but, like wildlife corridors, the ecological aspects have been poorly researched.

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REFERENCES

Aanen, P., Alberts, W., Bekker, G.J., van Bohemen, H.D., Melman, P.J.M., van der Sluijs, J., Veenbaas, G., Verkaar, H.J. & van de Watering, C.F. (1991) *Nature engineering and civil engineering works*, p. 139. Pudoc, Wageningen, The Netherlands.

Abensperg-Traun, M., Smith, G.T., Arnold, G.W. & Steven, D.E. (1996) The effects of habitat fragmentation and livestock-grazing on animal communities in remnants of gimlet *Eucalyptus salubris* woodland in the Western Australian wheatbelt. 1. Arthropods. *J. appl. Ecol.* **33**, 1281–1301.

Adams, L.W. (1984) Small mammal use of an interstate highway median strip. *J. appl. Ecol.* **21**, 175–178.

Adams, L.W. & Geis, A.D. (1983) Effects of roads on small mammals. *J. appl. Ecol.* **20**, 403–415.

Amor, R.L. & Stevens, P.L. (1975) Spread of weeds from a roadside into sclerophyll forests at Dartmouth, Australia. *Weed Res.* **16**, 111–118.

Andrews, A. (1990) Fragmentation of habitat by roads and utility corridors: a review. *Aust. Zool.* **26**, 130–141.

Angold, P.G. (1997) The impact of a road upon adjacent heathland vegetation: effects on plant species composition. *J. appl. Ecol.* **34**, 409–417.

Atkinson, R.B. & Cairns, J. (1992) Ecological risks of highways. *Advances in modern environmental toxicology: predicting ecosystem risk*, **20**, 237–262.

Backhaus, B. & Backhaus, R. (1987) Distribution of range transported lead and cadmium in spruce stands affected by forest decline. *Sci. total Environ.* **59**, 283–290.

Baker, B. (1998) Rethinking roads in the nation's forests. *BioScience*, **48**, 156.

Bakowski, C. & Kosakiewicz, M. (1988) Effects of a forest road on Bank Vole and Yellow-neck populations. *Acta theriol.* **72**, 245–252.

Ball, J.E., Jenks, R. & Aubourg, D. (1998) An assessment of the availability of pollutant constituents on road surfaces. *Sci. total Environ.* **209**, 243–254.

Baur, A. & Baur, B. (1990) Are roads barriers to dispersal in the land snail *Arianta arbustorum*? *Can. J. Zool.* **68**, 613–617.

Bekker, G.J., van den Hengel, B., van Bohemen, H.D. & van der Sluijs, H. (1995) *Nature across motorways*, p. 103. RWS & DWW., Delft.

Belsky, A.J. (1987) Revegetation of natural and human-caused disturbances in the Serengeti National Park, Tanzania. *Vegetatio*, **70**, 51–60.

Bennett, A.F. (1991) Roads, roadsides and wildlife conservation: a review. *Nature conservation 2: the role of corridors* (ed. by D.A. Saunders and R.J. Hobbs), pp. 99–118. Surrey Beatty & Sons Pty Limited, Western Australia.

Bernardino, F.S. & Dalrymple, G.H. (1992) Seasonal activity and road mortality of the snakes of the Pa-hay-okee wetlands of Everglades National Park, U.S.A. *Biol. Conserv.* **62**, 71–75.

Bohemem, H.D. van (1995) Mitigation and compensation of habitat fragmentation caused by roads: strategy, objectives, and practical measures. *Transpn Res. Rec.* **1475**, 133–137.

Box, J.D. & Forbes, J.E. (1992) Ecological considerations in the environmental assessment of road proposals. *Highways Transp.* April, 16–22.

Braun, S. & Fluckiger, W. (1984) Increased population of the aphis *Aphis pomi* at a motorway. Part 2—The effect of drought and deicing salt. *Environ. Pollut. (Series A)*, **36**, 261–270.

Brody, A.J. & Pelton, M.R. (1989) Effects of roads on Black Bear movements in western North Carolina. *Wild. Soc. Bull.* **17**, 5–10.

Brothers, T.S. & Spingarn, A. (1992) Forest fragmentation and alien plant invasion of central Indiana old-growth forests. *Conserv. Biol.* **6**, 91–100.

Burnett, S.E. (1992) Effects of a rainforest road on movements of small mammals: mechanisms and implications. *C.S.I.R.O. Wildl. Res.* **19**, 95–104.

Canaday, C. (1996) Loss of insectivorous birds along a gradient of human impact in Amazonia. *Biol. Conserv.* **77**, 63–71.

Case, R.M. (1978) Interstate highway road-killed animals: a data source for biologists. *Wild. Soc. Bull.* **6**, 8–13.

Cheshire Ecological Services (1995) *Cheshire roadside verge survey, Vol. 1, Report and recommendations*, p. 34. Cheshire Ecological Services, The Cheshire Wildlife Trust.

Clark, W.D. & Karr, J.R. (1979) Effects of highways on

Red-winged Blackbird and Horned Lark populations. *Wilson Bull.* **91**, 143–145.

Clifford, H.T. (1959) Seed dispersal by motor vehicles. *J. Ecol.* **47**, 311–315.

Clinnick, P.F. (1985) Buffer strip management in forest operations: a review. *Aust. For.* **48**, 34–45.

Cowie, I.D. & Werner, P.A. (1993) Alien plant species invasive in Kakadu National Park, tropical northern Australia. *Biol. Conserv.* **63**, 127–135.

Cuperus, R., Canters, K.J. & Piepers, A.A.G. (1996) Ecological compensation of the impacts of a road. Preliminary method for the A50 road link (Eindhoven-Oss), The Netherlands. *Ecol. Eng.* **7**, 327–349.

Davison, A.W. (1971) The effects of de-icing salt on roadside verges. 1, soil and plant analysis. *J. appl. Ecol.* **8**, 555–561.

Department of Transport (U.K.) (1992) *Assessing the environmental impact of road schemes*, p. 30. Her Majesty's Stationery Office, London.

Department of Transport (Scottish Office Industry Department), Welsh Office, Department of the Environment for Northern Ireland (1993) *Design manual for roads and bridges, Vol. 10: environmental design; Vol. 11: Environmental assessment*, p. 62. HMSO.

Dhindsa, M.S., Sandhu, J.S., Sandhu, P.S. & Toor, H S. (1988) Roadside birds in Punjab (India): relation to mortality from vehicles. *Env. Conserv.* **15**, 303–310.

Dochinger, L.S. (1980) Interception of airbourne particles by tree planting. *J. Environ. Qual.* **9**, 265–268.

Dowler, R.C. & Swanson, G.A. (1982) High mortality of Cedar Waxwings associated with highway plantings. *Wilson Bull.* **94**, 602–603.

Edmunds, J. (1995) *Head on collision 1995. Threats to important wildlife sites from road development in Cumbria, Lancashire, Merseyside, Greater Manchester and Cheshire*, p. 40. The Wildlife Trusts, North West England.

Environmental Resources Management (1996) The significance of secondary effects from roads and road transport on nature conservation. *English Nature Research Report No. 178*, p. 91. English Nature, Peterborough.

Erickson, P.A., Camagis, G. & Robbins, E.J. (1978) *Highways and ecology: impact assessment and mitigation*, p. 182. Prepared for the Federal Highway Administration (FHWA-RWE/OEP-78-2). National Technical Information Services, US Department of Commerce, Virginia, U.S.A.

Evink, G.L. (1990) Wildlife crossings of Florida I-75. *Transp. Res. Rec.* **1279**, 54–59.

Fahrig, L., Pedlar, J.H., Pope, S.E., Taylor, P.D. & Wegner, J.F. (1995) Effect of road traffic on amphibian density. *Biol. Conserv.* **73**, 177–182.

FAO (1989) Definition and scope of protective measures for roads. *Watershed Management Field Manual—Road design and construction in sensitive watersheds.* FAO Conservation Guide 13/5, pp. 1–12. Food and Agriculture Organisation of the United Nations, Rome.

Farmer, A.M. (1993) The effects of dust on vegetation—a review. *Environ. Pollut.* **79**, 63–75.

Feldhamer, G.A., Gates, J.E., Harman, D.M., Loranger, A.J. & Dixon, K.R. (1986) Effects of instate fencing on White-Tailed Deer activity. *J. Wildl. Mgmnt*, **50**, 497–503.

Ferris, C.R. (1979) Effects of Interstate 95 on breeding birds in northern Maine. *J. Wildl. Mgmnt*, **43**, 421–427.

Forbes, B.C. (1992) Tundra disturbance studies. 1: long-term effects of vehicles on species richness and biomass. *Environ. Conserv.* **19**, 48–58.

Forbes, B.C. (1995) Tundra disturbance studies, III: short term effects of Aeolian sand and dust, Yamal Region, Northwest Siberia. *Environ. Conserv.* **22**, 335–344.

Forman, R.T.T. (1995) Corridor attributes, roads, and powerlines. *Land mosaics: the ecology of landscapes and regions*, pp. 145–176. Cambridge University Press, Cambridge.

Garland Jr., T. & Bradley, W.G. (1984) Effects of a highway on Mojave Desert rodent populations. *Am. Midl. Nat.* **111**, 49–56.

Getz, L.L., Cole, F.R. & Gates, D.L. (1978) Interstate roadsides as dispersal routes for *Microtus pennsylvanicus. J. Ecol.* **59**, 208–213.

Gilbert, O.L. (1989) Roads. *The ecology of urban habitats*, pp. 145–164. Chapman and Hall Ltd., New York.

Gjessing, E., Lygren, E., Andersen, S., Berglind, L., Carlberg, G., Efraimsen, H., Källqvist, T. & Martinsen, K. (1984) Acute toxicity and chemical characteristics of moderately polluted runoff from highways. *Sci. total Environ.* **33**, 225–232.

Greszta, J. (1982) Accumulation of heavy metals by certain tree species. *Urban ecology—The second European Ecological Symposium Berlin, 8–12 September 1980* (ed. by R. Bornkamm, J.A. Lee and M.R.D. Seaward), pp. 161–165. Blackwell Scientific Publications, Oxford.

Haigh, M.J., Rawat, J.S., Rawat, M.S., Bartarya, S.K. & Rai, S.P. (1995) Interactions between forest and landslide activity along new highways in the Kumaun Himalaya. *For. Ecol. Mgmnt*, **78**, 173–189.

Hansen, K. & Jensen, J. (1972) The vegetation on roadsides on Denmark: a qualitative and quantitative comparison. *Dansk bot. Ark.* **28**, 2.

Havlin, J. (1987) Motorways and birds. *Folia zool.* **36**, 137–153.

Hellawell, J.M. (1988) Toxic substances in rivers and streams. *Environ. Pollut.* **50**, 61–85.

Hill, D. (1992) *The impact of noise and artificial light on waterfowl behaviour: a review and synthesis of available literature*, p. 32. British Trust for Ornithology, Tring.

Hodgen, R. & Ford, C.D. (1985) The planning, design and construction of a bypass through an area of outstanding natural beauty. *Proc. Inst. Civil Engrs*, **78**, 1065–1083.

Horner, R.R. & Mar, B.W. (1983) Guide for assessing water-quality impacts of highway operations and maintenance. *Transpn Res. Rec.* **948**, 47–55.

Howarth, L.S. (1991) Highway construction and wetland loss: mitigation banking programs on the southeastern

United States. *The Environmental Professional*, **13**, 139–144.
Hunt, A., Dickens, H.J. & Whelan, R.J. (1987) Movement of mammals through tunnels under railway lines. *Aust. Zool.* **24**, 89–93.
IEA (1995) *Guidelines for baseline ecological assessment*, p. 140. Institute of Environmental Assessment & E & FN Spon, London.
Illner, H. (1992a) Effect of roads with heavy traffic on Grey Partridge (*Perdix perdix*) density. *Gibier Faune Sauvage*, **9**, 467–480.
Illner, H. (1992b) Road deaths of Westphalian owls: methodological problems, influence of road type and possible effects on population levels. *The ecology and conservation of European owls* (ed. by I.R. Galbraith, I.R. Taylor and S. Percival), pp. 94–100. Joint Nature Conservation Committee, Peterborough. (UK Nature Conservation No. 5).
IUCN (1996) *Tourism, ecotourism and protected areas*, p. 284 IUCN, Gland.
Johnson, N.P. (1990) Nesting Bald Eagles (*Haliaeetus leucocephalus*) in urban areas of southeast Alaska: assessing highway construction and disturbance impacts. *Transpn Res. Rec.* **1279**, 60–68.
Kammerbauer, H., Selinger, H., Rommelt, R., Ziegler Jons, A., Knoppik, D. & Hock, B. (1986) Toxic effects of exhaust emissions on spruce *Picea abies* and their reduction by the catalytic converter. *Environ. Pollut. (Series A)*, **42**, 133–142.
Kearsley, G.W. (1990) Tourism development and user's perceptions of wilderness in southern New Zealand. *Aust. Geogr.* **21**, 127–140.
Kober, W.W. & Kehler, S.E. (1987) An analysis of design features in mitigating highway construction impacts on streams. *Transpn Res. Rec.* **1127**, 50–60.
Korn, H. (1991) Rapid repopulation by small mammals of an area isolated by roads. *Mammalia*, **55**, 629–632.
Kupfer, J. (1996) Patterns and determinants of edge vegetation of a midwestern forest preserve. *Phys. Geog.* **17**, 62–76.
Lamont, B.B., Rees, R.G., Witkowski, E.T.F. & Whitten, V.A. (1994) Comparative size, fecundity and ecophysiology of roadside plants of *Banksia hookeriana*. *J. appl. Ecol.* **31**, 137–144.
Lane, D. (1976) The vegetation of roadsides and adjacent farmland of the Mornington Peninsula, Victoria, Australia. *Weed Res.* **16**, 385.
Langton, T.E.S., (Ed). (1989) *Amphibians and roads. Proceedings of the Toad Tunnel Conference, Rendsberg, FRG, January 1989*, p. 202. ACO Polymer Products Ltd., Shefford, England.
Larwood, J.G. & Markham, D. (1995) *Roads and geological conservation—a discussion document*, 28 English Nature, Peterborough.
Laursen, K. (1981) Birds on roadside verges and the effect of mowing on frequency and distribution. *Biol. Conserv.* **20**, 59–68.
Leedy, D.L., (1978) Highways and wildlife: implications for management. *Classification, inventory, and analysis of fish and wildlife habitat—The Proceedings of a National Symposium*, pp. 363–383. Fish and Wildlife Service, US Department of the Interior, Maryland.
Lelièvre, M. & Sérodes, J.B. (1995) A new approach for the identification of environmental issues at stake in a roading project. *J. Environ. Mgmnt*, **44**, 221–231.
Lister, D.B. (1992) The argument for mitigation—case studies of impact mitigation concerning Anadromous Salmonid habitat. *Am. Fish. Soc. Symp.* **13**, 115–124.
Lonsdale, W.M. & Lane, A.M. (1994) Tourist vehicles as vectors of weed seeds in Kakadu National Park, northern Australia. *Biol. Conserv.* **69**, 277–283.
Macdonald, I.A.W. & Frame, G.W. (1988) The invasion of introduced species into nature reserves in tropical savannas and dry woodlands. *Biol. Conserv.* **44**, 67–93.
Macdonald, I.A.W., Loope, L.L., Usher, M.B. & Hamann, O. (1989) Wildlife conservation and the invasion of nature reserves by introduced species: a global perspective. *Biological invasions—a global perspective* (ed. by J.A. Drake, H.A. Mooney, F. di Castri, R.H. Groves, F.J. Kruger, M. Rejmanek and M. Williamson), pp. 215–255. SCOPE & John Wiley & Sons, New York.
Maddison, D., Pearce, D., Johansson, O., Calthrop, E., Litman, T. & Verhoef, E. (1996) *The true cost of road transport*, Blueprint 5, p. 192. Earthscan Publications Ltd, London.
Mader, H.J. (1984) Animal habitat isolation by roads and agricultural fields. *Biol. Conserv.* **29**, 81–96.
Mader, H.J., Schell, C. & Kornacker, P. (1990) Linear barriers to arthropod movements in the landscape. *Biol. Conserv.* **54**, 209–222.
Madsen, A.B. (1993) *Fauna passages in connection with large road systems, II. Hedgehogs, bats, birds and research of effects*, 53 pp. Miljøministeriet, Danmarks Miljøundersøgelser.
Madsen, A.B. (1996) *The ecology and conservation of the otter* (Lutra lutra) *in Denmark*. PhD thesis, Danmarks Miljøundersøgelser.
Majer, J.D. & Beeston, G. (1996) The Biodiversity Index: an illustration using ants in Western Australia. *Conserv. Biol.* **10**, 65–73.
Maltby, L., Forrow, D.M., Boxall, A.B.A., Calow, P. & Betton, C.I. (1995) The effects of motorway runoff on freshwater ecosystems: 1. Field study. *Environ. Toxicol. Chem.* **14**, 1079–1092.
Mansergh, I.M. & Scotts, D.J. (1989) Habitat continuity and social organisation of the mountain pygmy-possum restored by tunnel. *J. Wildl. Mgmnt*, **53**, 701–707.
Marrs, R.H., Frost, A.J., Plant, R.A. & Lunnis, P. (1992) The effects of herbicide drift on semi-natural vegetation: the use of buffer zones to minimize risks. *Aspects Appl. Biol.* **29**, 57–64.
Marsh, D.M. & Pearman, P.B. (1997) Effects of habitat fragmentation on the abundance of two species of Leptodactylid frogs in an Andean montane forest. *Conserv. Biol.* **11**, 1323–1328.
May, S A. & Norton, T.W. (1996) Influence of fragmentation and disturbance on the potential impact

of feral predators on native fauna in Australian forest ecosystems. *C.S.I.R.O. Wildl. Res.* **23**, 387–400.

Merriam, G., Kozakiewicz, M., Tsuchiya, E. & Hawley, K. (1989) Barriers as boundaries for metapopulations and demes of *Peromyscus leucopus* in farm landscapes. *Landsc. Ecol.* **2**, 227–235.

Michael, E.D. (1986) Use of roadside plantings by songbirds for nesting. *Transpn Res. Rec.* **1075**, 19–20.

Morris, P.A. & Morris, M.J. (1988) Distribution and abundance of hedgehogs (*Erinaceus europaeus*) on New Zealand roads. *N.Z. J. Zool.* **15**, 491–498.

Munguira, M.L. & Thomas, J.A. (1992) Use of road verges by butterfly and burnet populations, and the effect of roads on adult dispersal and mortality. *J. appl. Ecol.* **29**, 316–329.

Murphy, E.C. & Dowding, J.E. (1994) Range and diet of Stoats (*Mustela erminea*) in a New Zealand beech forest. *N.Z. J. Ecol.* **18**, 11–18.

Murphy, S.M. & Curatolo, J.A. (1987) Activity budgets and movement rates of caribou encountering pipelines, roads, and traffic in northern Alaska. *Can. J. Zool.* **65**, 2483–2490.

Muskett, C.J. & Jones, M.P. (1980) The dispersal of lead, cadmium and nickel from motor vehicles and effects on roadside invertebrate macrofauna. *Environ. Pollut.* **23**, 231–242.

Newbey, B.J. & Newbey, K.R. (1987) Bird dynamics of Foster Road Reserve, near Ongerup, Western Australia. *Nature conservation: the role of remnants of native vegetation* (ed. by D.A. Saunders, G.W. Arnold, A.A. Burbridge and A.J.M. Hopkins), pp. 341–343. Surrey Beatty & Sons Pty Ltd., Chipping Norton.

Nieuwenhuizen, W. & Apeldoorn, R.C. van (1995) *Mammal use of fauna passages on national road A1 at Oldenzaal*, p. 47. Directorate-General for Public Works and Water Management, Road and Hydraulic Engineering Division, Delft, The Netherlands.

Noss, R.F. (1995) *The ecological effects of roads, or the road to destruction*, pp. 11–21. Unpublished Report. Wildlands CPR, U.S.A.

Owens, L.K. & James, R.W. (1991) Mitigation of traffic mortality of endangered Brown Pelicans on coastal bridges. *Transpn Res. Rec.* **1312**, 3–14.

Oxley, D.J., Fenton, M.B. & Carmody, G.R. (1974) The effects of roads on populations of small mammals. *J. appl. Ecol.* **11**, 51–59.

Parr, T.W. & Way, J.M. (1988) Management of roadside vegetation: the long-term effects of cutting. *J. appl. Ecol.* **25**, 1073–1087.

Pedevillano, C. & Wright, R.G. (1987) The influence of visitors on mountain goat activities in Glacier National Park, Montana. *Biol. Conserv.*, **39**, 1–11.

Przybylski, Z. (1979) The effects of automobile exhaust gases on the Arthropods of cultivated plants, meadows and orchards. *Environ. Poll.* **19**, 157–161.

Queensland Department of Main Roads (1997) *Roads in the wet tropics. Planning, design, construction, maintenance and operation draft best practice manual*, Document No. 66515, p. 243. Gutteridge, Haskins & Davey Pty Ltd, Queensland.

Ramsay, D. (ed.) (1994) *Roads and nature conservation. Guidance on impacts, mitigation and enhancement*, 81 pp. English Nature, Peterborough.

Reed, D.F. (1981) Mule Deer behaviour at a highway underpass exit. *J. Wildl. Mgmnt*, **45**, 542–543.

Reed, R.A., Johnson-Barnard, J. & Baker, W.L. (1996) Contribution of roads to forest fragmentation in the Rocky Mountains. *Conserv. Biol.* **10**, 1098–1106.

Reid, J.W. & Bowles, I.A. (1997) Reducing the impacts of roads on tropical forests. *Environment*, **39**, 10–13.

Reijnen, R. & Foppen, R. (1994) The effects of car traffic on breeding bird populations in woodland. I. Evidence of reduced habitat quality for willow warblers (*Phylloscopus trochilus*) breeding close to a highway. *J. appl. Ecol.* **31**, 85–94.

Reijnen, R., Foppen, R., Ter Braak, C. & Thissen, J. (1995b) The effects of car traffic on breeding bird populations in woodland. III. Reduction of density in relation to the proximity of main roads. *J. appl. Ecol.* **32**, 187–202.

Reijnen, M.J.S.M., Veenbass, G. & Foppen, R.P.B. (1995a) *Predicting the effects of motorway traffic on breeding bird populations*, 92 pp. Road and Hydraulic Engineering Division & DLO—Institute for Forestry and Nature Research, Delft.

Reuter, J.E., Djohan, T. & Goldman, C.R. (1992) The use of wetlands for nutrient removal from surface runoff in a cold climate region of California—results from a newly constructed wetland at Lake Tahoe. *J. Environ. Mgmnt*, **36**, 35–53.

Reznicek, A.A. (1980) Halophytes along a Michigan roadside with comments on the occurrence of halophytes in Michigan. *Mich. Bot.* **19**, 23–30.

Rich, A.S., Dobkin, D.S. & Niles, L.J. (1994) Defining forest fragmentation by corridor width: the influence of narrow forest-dividing corridors on forest-nesting birds in Southern New Jersey. *Conserv. Biol.*, **8**, 1109–1121.

Roach, G.L. & Kirkpatrick, R.D. (1985) Wildlife use of roadside woody plantings in Indiana. *Transpn Res. Rec.* **1016**, 11–15.

Robinson, G.R. & Quinn, J.F. (1992) Habitat fragmentation, species diversity, extinction, and design of nature reserves. *Applied population biology* (ed. by S.K. Jain and L.W. Botsford), pp. 223–248. Kluwer Academic Publishers, Dordrechdt.

Rodriguez-Flores, M. & Rodriguez-Castellón, E. (1982) Lead and cadmium levels in soil and plants near highways and their correlation with traffic density. *Environ. Pollut. (Series B)*, **4**, 281–290.

Romin, L.A. & Bissonette, J.A. (1996) Deer-vehicle collisions: status of state monitoring activities and mitigation efforts. *Wild. Soc. Bull.* **24**, 276–283.

Salisbury, R. (1996) *A design for studying edge effects in forests*, Working Paper 9606, p. 32. Graduate School of the Environment, Macquarie University, Sydney, Australia.

Salvig, J.C. (1991) *Faunapassager i forbindelse med storre* *vejanlaeg*, Faglig rapport fra DMU, nr. 28, p. 67. Danmarks Miljoundersogelser.

Samways, M.J. (1989) Insect conservation and landscape ecology: a case-history of Bush Crickets (Tettigoniidae) in southern France. *Environ. Conserv.* **16**, 217–226.

Sangwine, A.P. (1992) The establishment and management of roadside planting. *Aspects Appl. Biol.* **29**, 195–201.

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

Saunders, D.A. & Hobbs, R.J. (1991) *Nature conservation 2: the role of corridors*, 442 pp. Surrey Beatty, Chipping Norton.

Saunders, D.A., Hobbs, R.J. & Ehrlich, P.R. (1993) *Nature conservation 3: reconstruction of fragmented ecosystems*, 326 pp. Surrey Beatty, Chipping Norton.

Scanlon, P.F. (1987) Heavy metals in small mammals in roadside environments—implications for food chains. *Sci. total Environ.* **59**, 317–323.

Schmidt, W. (1989) Plant dispersal by motor cars. *Vegetatio*, **80**, 147–152.

Schmitt, R.J. & Osenberg, C.W. (1996) *Detecting ecological impacts: concepts and applications in coastal habitats*, 401 pp. Academic Press, San Diego.

Schonewald-Cox, C. & Buechner, M. (1992) Park protection and public roads. *Conservation Biology—the theory and practice of nature conservation, preservation and management* (ed. by P.L. Fiedler and S.K. Jain), pp. 373–395. Chapman Hall, New York.

Seabrook, W.A. & Dettmann, E.B. (1996) Roads as activity corridors for Cane Toads in Australia. *J. Wildl. Mgmnt*, **60**, 363–368.

Sherburne, J. (1985) Wildlife populations utilizing right-of-way habitat along Interstate 95 in northern Maine. *Transpn Res. Rec.* **1016**, 16–20.

Singer, F.J., Langlitz, W.L. & Samuelson, E.C. (1985) Design and construction of highway underpasses used by mountain goats. *Transpn Res. Rec.* **1016**, 6–10.

Sinnadurai, S. (1981) High pressure sodium street lights affect crops in Ghana. *World crops* (Nov/Dec), 120–122.

Smith, D.S. (1993) Greenway case studies. *Ecology of greenways—design and function of linear conservation areas* (ed. by D.S. Smith and P. Hellmund), pp. 161–208. University of Minnesota Press, Minneapolis.

Smith, W.H. (1976) Lead contamination of the roadside ecosystem. *J. Air Pollut. Control Ass.* **26**, 753–765.

Southerland, M.T. (1995) Conserving biological diversity in highway devlopment projects. *The Environmental Professional*, **17**, 226–242.

Spellerberg, I.F. (1991) Biogeographical basis for conservation. *The scientific management of temperate communities for conservation*. 31st Symposium of the British Ecological Society (ed. by I.F. Spellerberg, F.B. Goldsmith and M.G. Morris), pp. 293–322. Blackwell Scientific Publications, Oxford.

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

Spellerberg, I.F. & Morrison, T. (1998) The ecological effects of new roads – a literature review. *Science for Conservation, 84.* Department of Conservation, Wellington, New Zealand.

Spencer, H.J. & Port, G.R. (1988) Effects of roadside conditions on plants and insects. II. Soil conditions. *J. appl. Ecol.* **25**, 709–715.

Swift, L.W. (1986) Filter Strip widths for forest roads in the southern Appalachians. *South. J. appl. For.* **10**, 27–34.

Swihart, R.K. & Slade, N.A. (1984) Road crossing in *Sigmodon hispidus* and *Microtus ochrogaster. J. Mammal.* **65**, 357–360.

Thompson, J.R., Rutter, A.J. & Ridout, P.S. (1986) The salinity of motorway soils II. Distance from the carriageway and other sources of local variation in salinity. *J. appl. Ecol.* **23**, 269–280.

Thrasher, M.H. (1983) Highway impacts on wetlands: assessment, mitigation, and enhancement measures. *Transpn Res. Rec.* **948**, 17–20.

Timmins, S.M. & Williams, P.A. (1990) Reserve design and management for weed control. *Alternatives to the chemical control of weeds* (ed. by C. Bassett, L.J. Whitehouse and J.A. Zabkiewicz), FRI Bulletin 155, pp. 133–138. Ministry of Forestry, Forest Reseach Institute, Rotorua, New Zealand.

Transfund NZ (1997) *Project evaluation manual*, No. PFM2, p. 201. Transfund New Zealand, Wellington.

Travis, M.D. & Tilsworth, T. (1986) Fish passage through Poplar Grove Creek Culvert, Alaska. *Transpn Res. Rec.* **1075**, 21–26.

Trimble, G.R. & Sartz, R.S. (1957) How far from a stream should a logging road be located? *J. For.* May, 1957, 339–341.

Tyser, R.W. & Worley, C.A. (1992) Alien flora in grasslands adjacent to road and trail corridors in Glacier National Park, Montana (U.S.A.). *Conserv. Biol.* **6**, 253–262.

U.S. Department of the Interior (1996) EIS No. 960048, *Final EIS, NPS, MI, Beaver Basin Rim Road Project*, 476 pp. U.S. Department of the Interior, National Park Service, Michigan.

Usher, M.B. (1987) Effects of fragmentation on communities and populations: a review with applications to wildlife conservation. *Nature conservation: the role of remnants of native vegetation* (ed. by D.A. Saunders, G.W. Arnold, A.A. Burbidge and A.J.M. Hopkins), pp. 103–121. Surrey Beatty & Sons Pty. Ltd., Chipping Norton.

Usher, M.B. (1988) Biological invasions of nature reserves: a search for generalisations. *Biol. Conserv.* **44**, 119–135.

Verboom, J. (1995) *Dispersal of animals and infrastructure. A model study: summary*, p. 8. Directorate-General for Public Works and Water Management, Road and Hydraulic Engineering Division, Delft, The Netherlands.

Vermeulen, H.J.W. (1994) Corridor function of a road verge for dispersal of Stenotopic Heathland Ground Beetles Carabidae. *Biol. Conserv.* **69**, 339–349.

Vestjens, W.J.M. (1973) Wildlife mortality on a road in New South Wales. *Emu*, **73**, 107–112.

Vos, C.C. & Chardon, J.P. (1998) Effects of habitat fragmentation and road density on the distribution pattern of the moor frog *Rana arvalis. J. appl. Ecol.* **35**, 44–56.

Wace, N. (1977) Assessment of dispersal of plant species—the car-borne flora in Canberra. *Exotic species in Australia—their establishment and success* (ed. by D. Anderson), Volume 10. *Proc. Ecol. Soc. Austl.* pp. 167–186.

Walker, D.A. & Everett, K.R. (1987) Road dust and its environmental impact on Alaskan Taiga and Tundra. *Arct. Alp. Res.* **19**, 479–489.

Ward, A.L. (1982) Mule Deer behaviour in relation to fencing and underpasses on Interstate 80 in Wyoming. *Transpn Res. Rec.* **859**, 8–13.

Ward, N.I., Brooks, R.R. & Reeves, R.D. (1974) Effect of lead from motor vehicle exhausts on trees along a major thoroughfare in Palmerston North, New Zealand. *Environ. Pollut.* **6**, 149–158.

Warner, R.E. (1985) Demography and movements of free-ranging domestic cats in rural Illinois. *J. Wildl. Mgmnt*, **49**, 340–346.

Warner, R.E. (1992) Nest ecology of grassland passerines on road rights-of-way in central Illinois. *Biol. Conserv.* **59**, 1–7.

Watkins, L.H. (1981) *Environmental impact of roads and traffic*, 268 pp. Applied Science Publishers, London.

Watson, V.J., Rice, P.M. & Monnig, E.C. (1989) Environmental fate of Picloram used for roadside weed control. *J. Environ. Qual.* **18**, 198–205.

Way, J.M. (1977) Roadside verges and conservation in Britain: a review. *Biol. Conserv.* **12**, 65–74.

Wells, M., Langton, T., Garland, L. & Wilson, G. (1996) The value of motorway verges for reptiles—a case study. *Reptile survey methods: proceedings of a seminar, November 1995 at the Zoological Society of London* (ed. by J. Foster and T. Gent), English Nature Science No. 27, pp. 174–181. English Nature, Peterborough.

Weste, G. (1977) Future forests—to be or not to be. *Victoria's Resources*, **19**, 26–27.

Wester, L. & Juvik, J.O. (1983) Roadside plant communities on Mauna Loa, Hawaii. *J. Biogeogr.* **10**, 307–316.

Westing, A.H. (1969) Plants and salt in the roadside environment. *Phytopathology*, **59**, 1174–1181.

Wilcox, D.A. (1989) Migration and control of purple loosetrife (*Lythrum salicaria* L.) along highway corridors. *Environ. Mgmnt*, **13**, 365–370.

Wilcox, B.A. & Murphy, D.D. (1985) Conservation strategy: the effects of fragmentation on extinction. *Am. Nat.* **125**, 879–887.

Williams-Linera, G. (1990) Vegetation structure and environmental conditions of forest edges in Panama. *J. Ecol.* **78**, 356–373.

Wilson, J.B., Rapson, G.L., Sykes, M.T., Watkins, A.I. & Williams, P.A. (1992) Distributions and climatic correlations of some exotic species along roadsides in South Island, New Zealand. *J. Biogeogr.* **19**, 183–194.

Wong, M.H., Cheung, Y.H. & Wong, W.C. (1984) Effects of roadside germination and root growth of *Brassica chinensis* and *B. Parachinensis. Sci. total Environ.* **33**, 87–102.

World Bank (In press) *Roads and the environment.* The World Bank, Environmentally sustainable development Vice-Presidency, p. 203. Transportation, Water & Urban Development Department, Transport Division, Washington.

Yanes, M., Velasco, J.M. & Suarez, F. (1995) Permeability of roads and railways to vertebrates: the importance of culverts. *Biol. Conserv.* **71**, 217–222.

Young, A. & Mitchell, N. (1994) Microclimate and vegetation edge effects in a fragmented podocarp-broadleaf forest in New Zealand. *Biol. Conserv.* **67**, 63–72.

Yousef, Y.A., Baker, D.M. & Hvitved-Jacobsen, T. (1996) Modeling and impact of metal accumulation in bottom sediments of wet ponds. *Sci. total Environ.* **189/190**, 349–354.

Zande, A.N. van der, Keurs, W.J. teu & Weijden, W.J. van der (1980) The impact of roads on the densities of four bird species in an open field habitat—evidence of a long-distance effect. *Biol. Conserv.* **18**, 299–321.