# Ecological effects of roads: Toward three summary indices and an overview for North America

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## Abstract

*An extensive road network with vehicles in North America exerts dozens of direct ecological effects, which may be effectively assayed or represented by three broad variables or indices.*

1. **Road density** *exhibits an apparent threshold of ca. 0.6 km/km$^2$ (1.0 mi/mi$^2$), above which natural populations of certain large vertebrates decline.*
2. **Road location** *primarily measures the degree of avoidance of large natural-vegetation patches, major wild-life connectors, riparian zones, and rare habitats and species.*
3. **A road-effect zone** *over which ecological effects extend is many times wider than the road (with roadsides/verges), and is strongly asymmetrical with convoluted margins. Surprisingly few rare animal species are known to be threatened by roads in North America, perhaps due to a major research gap. Except for faunal underpasses, mitigation structures for animals to cross roads are rare. We conclude that a quantum leap in focus on the ecological effects of roads is warranted, and that the foundations are in place for effective research, planning, public education, and action.*

## Introduction

Six million kilometers of public roads (including roadsides or verges) cover about one percent of the contiguous United States. Two hundred million vehicles use the roads. The ecological effects of these roads and vehicles cover a larger, but as yet undetermined, area across the nation.

The effects of roads (including highways) on habitat, species, soil and water are highly diverse, and vary in different landscapes. For example, in suburban landscapes of the United States and Canada (Forman & Hersperger 1996),

1. the road network removes and dissects scarce natural habitat, leaving nature fragmented, and
2. traffic noise levels reduce biodiversity for considerable distances, particularly for birds (Reijnen et al. 1995).

In open landscapes (e.g., agriculture and desert),

1. roads disrupt species movement, especially in wildlife corridors,
2. new roads lead to development, and thus loss of key habitats, species, and natural flows,

3. roadkills (faunal casualties or animal mortality by vehicles) threaten a few rare populations, and
4. introduced exotic species and pests invade nearby land (Saunders & Hobbs 1991).

In forested landscapes,

1. roads penetrate remote areas, with human disturbance reducing wildlife, habitat quality and bio-diversity,
2. the road network disrupts natural flows across the landscape, such as groundwater and fire,
3. road ditches and culverts lead to higher peak flows of streams and rivers, causing floods, damage, and floodplain changes (Jones & Grant 1996),
4. road construction, usage and maintenance accelerate soil erosion and sedimentation, and
5. runoff from roads increases stream sedimentation, pollution and fish loss.

These three groups of impacts also emphasize that the primary ecological problems, plus their solutions, differ markedly in the three basic types of landscapes, suburban, open, and forested.

Almost all these effects are mainly due to roads, that is, the infrastructure or network in place. However, vehicle usage plays a major role in traffic noise and roadkill effects, and a secondary role in disrupting species movement and disturbing remote areas.

In addition, vehicle emissions cause atmospheric pollution and consequent ecological effects (Winner 1994). Nitrogen oxide increases nitrogen input, plant growth and damage proneness in ecosystems. Tropospheric ozone damages trees. Greenhouse gases and particulates cause changes in climate, vegetation, and production.

The preceding processes are so extensive that it is difficult to envision or compare the relative cumulative impact of roads. Therefore the first major objective of this article is to identify three concepts or indices that may effectively assay the diverse ecological effects of roads.

1. **Road density** is mainly examined for large vertebrates in forested landscapes.
2. **Road location** in a landscape is examined using proximity to patches and corridors of natural vegetation and to streams in hilly or mountainous terrain.
3. **The road-effect zone** extending outward from a road is examined for species, water and materials, which in turn are affected by directional processes across a landscape.

Although road effects on species, including rare species, and wildlife-crossing structures for mitigation are actively discussed, studied or used in Europe, rather little work has been done in North America. Therefore the second major objective of this article is to provide an overview of the situation in North America, based on a scattered literature.

Rare animal species significantly affected by roads, as well as existing mitigation structures for wildlife crossing of roads, are summarized.

Virtually all roads and all trips in a vehicle cut through many local ecosystems and land uses in the land mosaic. Thus the ecological effects of roads are effectively analyzed and understood in the context of landscape and regional ecology, including its patch-corridor-matrix theory (Forman 1995). Indeed, road corridors and networks are structural components of essentially all land mosaics. Movements along and outward from roads affect and are affected by the flows and movements of the functioning landscape. In addition, road construction, expansion, and removal are part of the many spatial changes of a dynamic landscape over time.

### Road density

Road density, e.g., measured as km/km$^2$ on a map, is proposed as a useful broad index of several ecological effects of roads in a landscape (Reck & Kaule 1993, Forman 1995). Particularly important are faunal movement, population fragmentation, human access, hydrology, and fire patterns. Six major patterns associated with a higher road density have been identified (Forman & Hersperger 1996):

1. Natural populations are reduced by habitat loss, due to road and roadside construction plus avoidance of areas near roads. Also populations of a few rare species are reduced by roadkills.
2. Populations are fragmented into smaller subpopulations, which are more subject to demographic fluctuation, inbreeding, loss of genetic variability, and local population extinction. However, to date very few studies relate genetic changes in populations to roads [e.g., the common frog *Rana temporaria* (Reh & Seitz 1990), key deer *Odocoileus virginianus clavium* (Calvo & Silvy 1996), Florida panther *Felis concolor coryi* in Florida (L.D. Harris, personal communication), and possibly the grizzly and mountain lion in Alberta (Gibeau & Heuer 1996)].
3. Human access to remote areas results in more hunting, disturbance of animals, trampling, and damage to natural ecosystems.
4. On moist slopes road culverts that are inadequate in size, location or number normally cause a higher water table upslope and a lower water table downslope. Also a road with an upslope cutbank and large roadside ditches and culverts may cause a lower water table both upslope and downslope.
5. Roadside ditches typically become connected to the stream network, resulting in significantly higher and earlier peak discharges, which in turn cause floods, damage and floodplain alterations (Jones & Grant 1996). Greater erosion and sedimentation also occurs.
6. With greater human access fires may increase in frequency. However, fire sizes decrease due to the road barrier effect and more efficient fire-fighting access.

Different species are readily compared for their sensitivity to roads using road density (Fig. 1). A road density of approximately 0.6 km/km$^2$ appears to be the maximum or threshold for a naturally functioning landscape containing sustained populations of wolves *Canis lupus* and mountain lions *Felis concolor* (Thiel 1985, Van Dyke et al. 1986, Jensen et al. 1986, Mech et al. 1988, Mech 1989). For comparison, the average density of public roads in the contiguous United States is 0.73 km/km$^2$ (1.2 mi/mi$^2$) (Stephen Godwin, personal communication), though of course variability from area to area is striking. Road density is thought to be important to other large vertebrates including moose *Alces alces* (Crete et al. 1981, Timmermann & Gallath 1982), white-tailed deer *Odocoileus virginianus* (Sage et al. 1983), brown bear *Ursus arctos* (Elgmork 1978), and perhaps grizzly *U. horribilis* (May 1994 American Forests and Nov. 21, 1994 Washington Post) and woodland caribou *Rangifer caribou* (Sept. 17, 1995 Toronto Star).

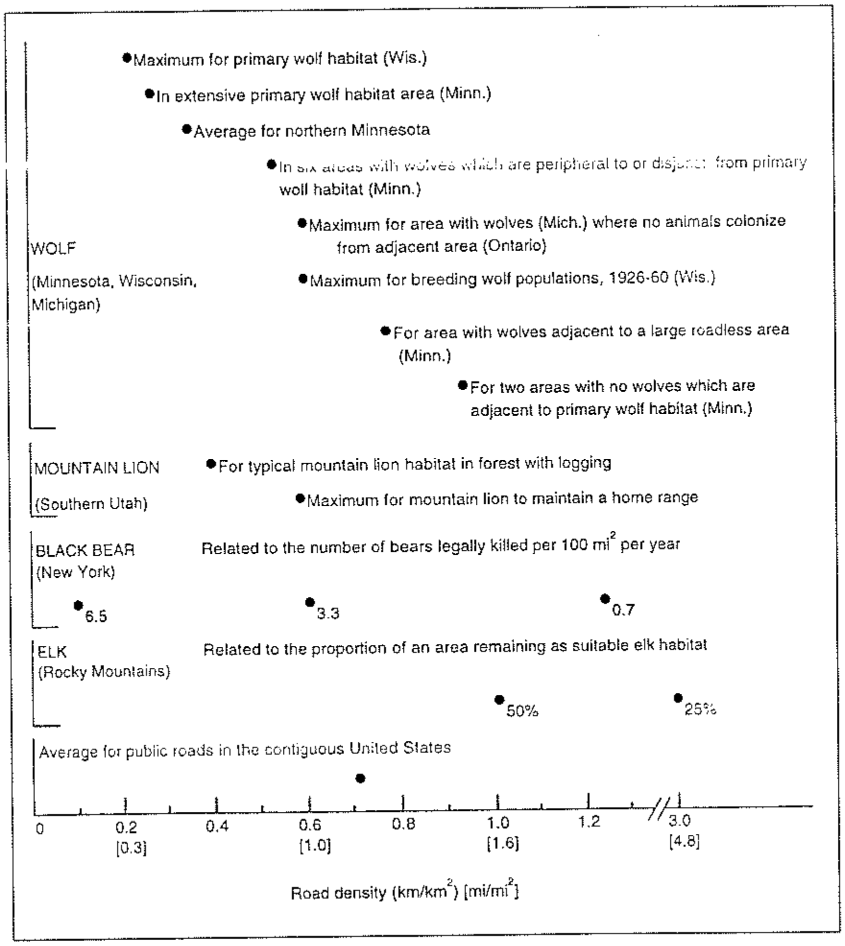


**Figure 1.**
Wildlife populations related to road density.
Wolf *Canis lupus* (Thiel 1985, Jensen et al. 1986, Mech et al. 1988, Mech 1989); elk *Cervus canadensis* (Rost & Bailey 1979, Lyon 1983); black bear *Ursus americanus* (Brocke et al. 1990); mountain lion *Felis concolor* (Van Dyke et al. 1986).
In the mainly forested counties of the Adirondack Mountains of New York, there are many times more bears in low than high road-density areas.

Hydrologic effects are evident at road densities of 2-3 km/km$^2$ in mountain drainage basins of Western Oregon. Peak discharges (and floods) in streams after storms are significantly higher with a road network present, compared with control basins with negligible road density (Jones & Grant 1996). Peak discharges also occur earlier after storms.

Three mechanisms may cause road density effects on animal populations: road avoidance; human access; and roadkills. Road avoidance, i.e., remaining distant from roads with vehicular disturbance, is characteristic of elk *Cervus canadensis* (Rost & Bailey 1979, Lyon 1983), bighorn sheep *Ovis canadensis* (Gibeau & Heuer 1996), grizzly (Woods & Munro 1996, Reudiger 1996), caribou (Woods & Munro 1996), and wolf (Paquet & Callaghan 1996). Avoidance distances of 100-200 m are common for these species, though up to 1 km is reported for grizzly (Boone & Hunter 1996).

In contrast, human access, primarily on tiny unpaved roads that permit hunters and vacationers to easily reach remote areas, contributes to the road-density response pattern for black bear *Ursus americanus* (Brody & Pelton 1989, Brocke et al. 1990), mountain lion (Van Dyke et al. 1986), and wolf (Mech 1977 1989). A decrease in desert tortoises *Gopherus agassizii* within ca. 0.6 km of a California Mojave Desert road may be due to road avoidance. However, it may well be due to roadkills (Boarman & Sazaki 1996). Therefore solutions that maintain or increase elk, black bear, and desert tortoises, representing road avoidance, human access, and roadkills, respectively, may be quite different.

This emphasizes that road density itself is an overall index or measure, which represents several more specific variables producing road density effects. These variables include road network connectivity, road type or width, and traffic density.

An index of variance or unevenness in mesh size or grain size is also important in understanding the road density effect (Forman 1995, Miller et al. 1996, Reed et al. 1996). A landscape with a moderately high road density but containing a roadless area may support sustained populations of wildlife, even though the average road density of the total landscape is excessive (Mech et al. 1988, Mech 1989). Indeed the presence of a few large areas of low road density (Rudis 1995) may be the best indicator of suitable habitat for large vertebrates.

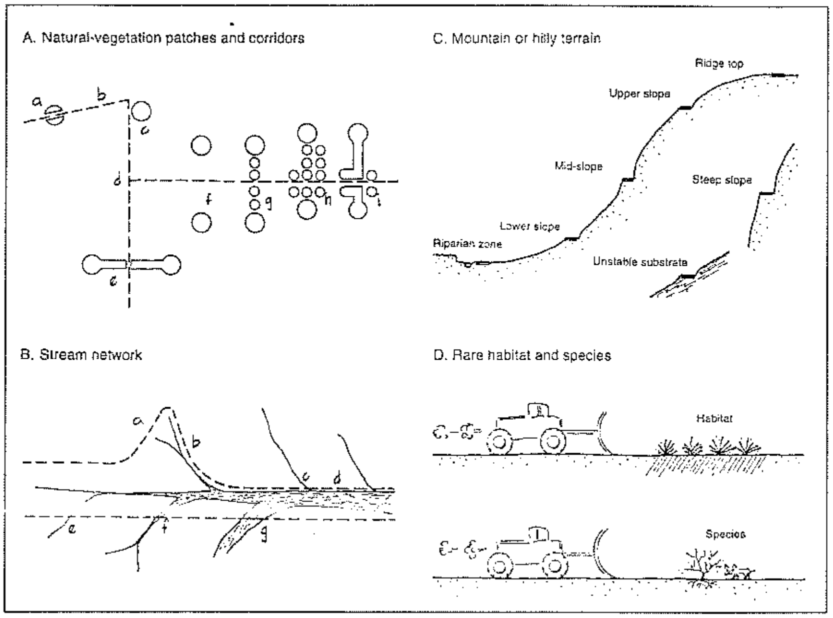
### Road Location

Four aspects of road location are especially important in evaluating ecological effects. These are portrayed by relating road arrangement to: large natural-vegetation patches and their corridors; streams of different sizes; topography; and rare habitats and species. A quantitative index for road location remains to be worked out.

*Natural-vegetation patches and corridors*

a. (See location a in Fig. 2A) A road bisecting a large patch of natural vegetation causes habitat loss, and degrades some of the remaining patch habitat by disturbance and the introduction of edge species.
b. A road connecting two patches strongly inhibits movement of interior species between them.
c. Disturbance, especially road noise affecting birds, extends some distance from an adjacent road and degrades some of the patch habitat.
d. A busy road intersection is well located away from a patch.
e. Cutting a vegetation corridor connecting two patches will reduce move-

**Figure 2.**
Four key dimensions for evaluating the ecological effects of road location. See text.



ment between the patches. A road reduces scarce corridor habitat plus road disturbance degrades adjacent corridor habitat.

f. Where no corridor exists, locating a road more than the road-disturbance distance from each patch does not degrade the patch habitats.
Note that the midpoint between patches probably has the least interior species movement, and there a road would be most damaging.

g. For species movement a row of small patches is considered better than location f and worse than e. If a road must cross between large patches of natural vegetation, a cluster of small patches between large patches

h. or some extra vegetation on opposite sides of a road by a corridor

i. are hypothesized to be the best patterns for species movement (Forman 1995).

*Stream network*

a. (See location a in Fig. 2B) A road that goes around a first-order headwaters stream commonly causes major damage to the small fragile basin or catchment by altering erosion, mineral nutrient runoff, and hydrologic flows into the stream system.

b. A road adjacent to a first-order stream causes similar effects, and next to a second- or third-order stream often has significant damaging effects on erosion, mineral nutrient input, sedimentation, streamwater quality, and fish populations.

c. A bridge at a stream intersection commonly disturbs riparian and stream species, sediment and water movement at a critical junction.

d. An adjacent road along a larger stream or small river typically damages streambank vegetation, floodplain processes and habitats, and stream ecosystems. In contrast, a road with bridges at locations e, f and g crosses rather than is adjacent to streams, and causes less ecological damage. Most effects here are immediately downstream of the bridges.

### *Topography*

The major ecological effects of road location are compared in hilly or mountainous terrain, ranging from ridgetop to riparian zone in a valley bottom (Fig. 2C). A ridgetop road may inhibit a wildlife movement corridor, increase human access and disturbance (such as fire and hunting) into a remote area, and result in damage to rare ridgetop species. An upper-slope road apparently has few negative ecological impacts. A midslope road may have considerable soil erosion, creep, slump and slides due to its relative steepness, plus an intermediate amount of surface and/or subsurface water flow. A lower-slope road, however, is commonly subject to considerable water flow. Cool groundwater is typically converted to warm surface water through cutbank seepage, ditch and culvert flow, and subsequent downslope flow. This increases erosion and mineral nutrient runoff, sedimentation and degraded streamwater, and fish population changes. A riparian-zone road causes numerous ecological alterations, such as streambank vegetation loss, fewer logs and branches for fish habitat, higher streamwater temperature, more erosion and sedimentation, less beaver activity, reduced biodiversity in floodplain habitats, and inhibition of species movement along the stream corridor. Steep slopes and those with unstable substrates (Fig. 2C) cause many erosion, nutrient, and sedimentation problems.

Clearly economic, visual, construction and safety issues are important in determining road location in hilly and mountainous terrain. Nevertheless, locations are readily compared in this generalized model for roads in place (Fig. 2C). Based on ecological considerations, the upper slope is the best location for a road, and the riparian, steep, and unstable-substrate locations are worst for a road.

### *Rare habitats and species*

Countless animals are annually killed on roads. However, documented roadkill rates are significant in reducing population sizes of only a small number of rare species in North America. Apparently no summary or evaluation has been published of either rare habitats or rare species in the United States that are significantly affected by roads (Fig. 2D). Thus the following list, although doubtless incomplete, provides an initial picture of the problem of roads and rare species. Most animals included are nationally (federally) listed as endangered or threatened, and in most cases a road significantly impacts a local population of the species.

1. Florida panther (mountain lion) *Felis concolor coryi*; U.S. endangered; South Florida; probably <75 remain; before 1991, 4-5 roadkills/yr, which was 47% of known deaths and the greatest known cause of humanrelated mortality; ca 1 roadkill/yr since underpasses were established ca. 1991 (Foster & Humphrey 1995, Smith et al. 1996).
2. Cougar (mountain lion) *Felis concolor*; Banff National Park, Alberta, the connector "genetic bridge" between populations east and west of the central Canadian Rocky Mountains; population ca. 4-7; one roadkill every 3-4 yr, or an average of 3-5% of the local population annually roadkilled over a 52-year period (Gibeau & Heuer 1996).
3. Ocelot *Felis pardalis*; U.S. endangered; Rio Grande Plains of South Texas; roadkills are considered the major cause of mortality (Jenkins 1996).

4. Key deer *Odocoileus virginianus clavium*, a small subspecies of the white-tailed deer; U.S. listed; islands at southern tip of Florida; population ca. 250-300; ca. 44 roadkills per year, which is 75-80% of all known deaths (Calvo & Silvy 1996).
5. Northern long-eared bat *Myotis septentrionalis*; Canada listed; Mount Revelstoke National Park, British Columbia; only known breeding location for the species is bisected by Trans-Canada Highway; mortality rate unknown (Woods & Munro 1996).
6. Texas subspecies of the eastern brown pelican *Pelecanus occidentalis*; South Texas and Port Isabel/Brownsville region; population ca. 75-100; 4-8 roadkills per year reported on 4-lane coastal causeway bridge (Jenkins 1996).
7. Royal tern *Sterna maxima*; Florida; bridge; mortality rate unknown (Evink 1996).
8. Barn owl *Tyto alba*; California's Central Valley; species declining in Southern California; since 1916 roadkills increasing in the Central Valley of Central California, and now appear to be the major cause of mortality here (Moore & Mangel 1996).
9. American crocodile *Crocodylus acutus*; U. S. endangered; Florida; roadkills are 46% of human-related mortality (Smith et al. 1996).
10. Desert tortoise *Gopherus agassizii*; U. S. threatened; Highway 58, Mojave Desert, California; one roadkill per 2.4 km of road per year (Ruby et al. 1994, Boarman & Sazaki 1996).
11. Houston toad *Bufo houstonensis*; U. S. endangered; State Road 21, Bastrop County, South Central Texas; amphibian tunnel installed; mortality rate unknown (Thomas Griebel, personal communication, Jenkins 1996).

Finally, roads strongly affect processes across the landscape (Harris et al. 1996). For example, the road network contributes significantly to reducing fire frequency in Florida where several U.S. endangered species are dependent on habitats maintained by fire (Stevenson 1996). Similarly freshwater mussels or clams might have the highest percentage of threatened species in the United States, and road networks overlaid on stream systems probably contribute significantly to this effect (Fig. 2B).

In short, road location is an important integrator or predictor of diverse ecological effects. Large natural-vegetation patches, connectivity between them, and major vegetated stream corridors are prime consideration in planning and conservation (Forman & Collinge 1995). But road locations relative to topography, rare habitats, and rare species are also of major importance.

### Road-effect Zone

Not surprisingly, the highly diverse ecological effects of roads vary widely in how far outward they extend from the road. These distances of significant impacts from the road surface have been summarized by Reck & Kaule (l993) and Forman (l995), and vary from a few meters to a few kilometers (Fig. 3).

However, the effects almost always extend different distances on opposite sides of the road. This pattern is due primarily to the directional processes and asymmetrical arrangements of slope, wind, and habitat suitability in the landscape. Thus slope mainly causes unequal effects for water and material carried by water (Fig. 3). Wind causes marked asymmetries in light-weight materials such as dust and salt, in addition to traffic noise effects.
Habitat suitability is especially important to species movements and to human access effects on opposite sides of a road. In essence, the road-effect zone is asymmetrical with highly convoluted borders.

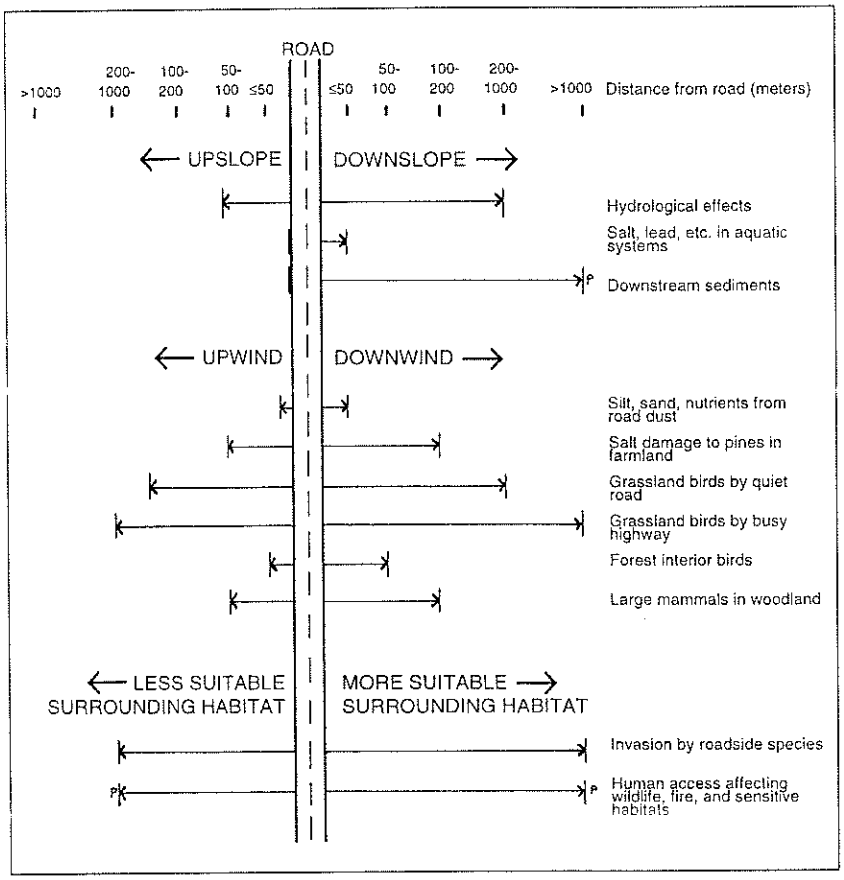


**Figure 3.**
Road-effect zone defined by ecological effects extending different distances from a road.
Most distances are based on specific studies (Forman 1995).
However, distance extending to left is arbitrarily half that to the right.
"P" indicates an effect primarily at specific points.

Most ecological effects are relatively continuous along a road. However, a few effects are concentrated at specific spots, such as sedimentation downstream of a bridge or hunting effects around a human access point in a remote area (Fig 3).

Finally, the road-effect zone is many times wider than the road surface with its roadsides. For example, let us assume that the average road and roadside is 30 m (e.g., road surface 10 m, plus the combined width of adjacent 10 m roadsides, which may include scraped, mowed, ditched, etc. areas) for the 6 million kilometers of public roads covering one percent of the contiguous United States. Then averaging the lengths of arrows in Fig. 3 provides a conservative estimate that direct ecological effects extend over a distance of 400 m width (some 200 m on each side of the road surface). Dividing 400 by 30 suggests that direct ecological effects extend over an area >10 times the road/roadside width, though note that both the numerator and denominator are rough estimates and that many variables are involved. Nevertheless, as a preliminary hypothesis, more than 10% of the contiguous United States is directly impacted ecologically by roads.

### Wildlife-crossing structures

Diverse mitigation structures from 0.2 to 200 m wide have been constructed to enhance movement of animals across roads (including highways) (Forman & Hersperger 1996). Most have been monitored and found to have wildlife species crossing. Most of the structures are in Europe. Therefore the following list, though probably incomplete, is presented as an overview of the wildlife-crossing structures existing in North America.

#### *Amphibian tunnels*

Two 25 cm wide tunnels on Henry Street in Amherst, Massachusetts enhance the huge spring migrations of spotted salamanders *Ambystoma maculatum* (Jackson 1996). One of these tunnels on State Highway 21 in Bastrop County, Texas was built for the U.S. endangered Houston toad *Bufo houstonensis*, and has had limited success (Thomas Griebel, personal communication; Jenkins 1996).

#### *Culverts and ecopipes*

Culverts along Highway 58 in the Mojave Desert of California vary from 0.9 to 3.6 m width, and from 33 to 66 m length. They are used by the desert tortoise, coyote *Canis latrans*, kit fox *Vulpes maerotis*, and jackrabbit *Lepus californicus* (Ruby et al. 1994, Boarman & Sazaki 1996). No reports have been located of ecopipes (like badger tunnels in Europe; Natuur over Wegen 1995), that is, pipes or tunnels designed for movement of mid-sized mammals, but not for water flow.

#### *Underpasses*

Best known are the 23 underpasses (plus 13 bridge extension locations) along Alligator Alley (Interstate Highway 75) in South Florida (Foster & Humphrey 1995). They are 21-26 m wide and 48.5 m long. They were primarily built to enhance groundwater flow to the Everglades, plus movement of Florida panthers across the highway. Two underpasses built nearby on Route 29 for panthers are 7.3 m wide and 14.3 m long (Land & Lotz 1996). One underpass of the same type was built primarily for black bears on Route 46 in Lake County, Central Florida (Roof & Wooding 1996). The objectives were apparently accomplished at all three highways. In addition, many other species also crossed regularly in underpasses at all three highways, including bobcat *Lynx rufus*, white-tailed deer, alligator *Alligator mississippiensis*, raccoon *Procyon lotor*, turkey, fox, otter *Lutra canadensis*, and black bear. Numerous species have crossed in the large underpasses of Interstate 75. Armadillo *Dasypus novemcinctus*, opossum *Didelphis virginiana*, rabbit, and gopher tortoise *Gopherus polyphemus* crossed in the Route 46 underpass (Evink 1996, Land 1996, Roof & Wooding 1996).

Also well studied are ten underpasses about a kilometer apart on the Trans-Canada Highway in Banff National Park, Alberta. These are 4 m high and vary from ca. 4 to 13 m wide (Leeson 1996). They are used by elk, grizzly, black bear, wolf, coyote, cougar, lynx *Lynx canadensis*, and bighorn sheep (Paquet & Callaghan 1996, Gibeau & Heuer 1996, Leeson 1996). Thirteen more underpasses are under construction as the highway is being extended.

Other underpasses function for mountain goats *Oreamnus americanus* in Glacier National Park, Montana (Singer & Doherty 1985) and mule deer in Colorado and Wyoming (Reed 1981, Ward 1982). Becker (1996) cites reports of underpass use by moose and mule deer in Idaho, Wyoming and California. Other reported wildlife underpasses are on Highway 52 in Southern California (Jan. 3, 1994 San Diego Union-Tribune) (apparently with limited success), on Forest Highway 39 near Tucson, Arizona (Mar. 22, 1995 Public Roads), two being built on the Fairfax County Parkway in Northern Virginia (May 31, 1995 Washington Post), and one to be built on the Evergreen Parkway in Colorado (Dec. 7, 1994 Rocky Mountain News).

### *Overpasses*

Although several overpasses or "ecoducts" designed for wildlife crossing (Natuur over Wegen 1995) operate in European countries, apparently New Jersey has the only existing wildlife overpasses in North America. Two 31 m wide overpasses cross a six-lane Interstate highway 78, which bisects the Watchung Reservation (a park) in Union County, New Jersey (Kuennen 1989). The tall flat-bottomed overpasses connect the two portions of the park, and are regularly crossed by white-tailed deer and other wildlife species. Horseback riders and hikers also cross on the overpasses.

Two 50 m wide overpasses 9 km apart are being built in the four-lane divided Trans-Canada Highway extension in Alberta (Leeson 1996). These are of double-vaulted construction based on three existing structures in Europe (Pfister & Keller 1995, Natuur over Wegen 1995). The Canadian overpasses are designed primarily for elk crossing, with hopes that grizzly and other animals will use them. Two 125 m long overpasses were planned for elk to cross the Evergreen Parkway in Colorado (Dec. 7, 1994 Rocky Mountain News).

### *Landscape connectors*

Since many processes operate across a landscape (Harris et al. 1996), rather than only focusing on specific animal movements, a broader ecological objective is a structure that permits all landscape flows and movements to cross a road. Thus landscape connectors (Forman and Hersperger 1996) in different places would permit crossing of groundwater, surface water, fire, soil and snow movement, foraging, animal dispersal, migration, pollination, seed dispersal, wind transport and so forth.

None exists in North America. The 140 and 200 m wide structures in Switzerland are the widest existant (Nationalstrasse N7 Mullheim-Schwaderloh 1992, Magnin 1994, Pfister & Keller 1995), though 1.5-1.7 km wide connectors are apparently planned in Switzerland and Holland. Perhaps the closest analogue in North America are the "avalanch tunnels" in the Rocky Mountains of British Columbia where avalanches roar harmlessly over highway and railway traffic (John Woods, personal communication). However, these are not designed, e.g., for wildlife and fire crossing.

Specialized mitigations for particular species are present in many states and provinces. These include bathouses on bridges in Austin, Texas (Tuttle 1995, Jenkins 1996), kestrel *Falco sparverius* nest boxes behind roadsigns on U.S. route 20 in Iowa (personal observation), holes for animal crossing in concrete "Jersey barriers" separating highway lanes on Cape Cod, Massachusetts (Hadrian Millon, personal communication), and special culvert designs for salmon migration in Washington (Cary & Wagner 1996).

In short, North America is well behind Europe in installing wildlife-crossing structures (Forman & Hersperger 1996), yet a range of structures from amphibian tunnels to overpasses exist here. Underpasses are most frequent. Monitoring indicates that target species as well as other wildlife use the structures to successfully cross roads and highways. However, crossing rates relative to population sizes and movements are essentially unknown.

## Conclusion

In the United States the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA: pronounced "ice-tea") for the first time requires state and regional transportation planning agencies to consider "the likely effect of transportation policy decisions on land use" and "the effects of all transportation projects to be undertaken within the metropolitan area, without regard to whether they are publicly funded." These effects include the environmental, social, economic and energy consequences of transportation decisions. Indeed, ISTEA opens with a Declaration of National Policy, "It is the policy of the United States to develop a National Intermodal Transportation System that is economically efficient and environmentally sound...", and which pays "particular attention to the external benefits of reduced air pollution, reduced traffic congestion and other aspects of the quality of life in the United States."

ISTEA requires that the regional transportation system have a high level of mobility for all people, and that it maintain standards for environmental quality (Falbel 1993). Thus the Act begins to bridge the gap between the societal needs of vehicular connection and the environmental costs associated with roads that fragment the landscape.

ISTEA's language also links ecological attributes with the aesthetics of a landscape, for example, in considering the effects of policy decisions on land use and development, acquisition of scenic easements, landscaping and other scenic beautification, and mitigation of water pollution due to highway runoff (Falbel 1993, California Transportation Commission 1995). Linking ecology to aesthetics has the advantage that transportation engineers and society have accepted a role for aesthetics in road construction and maintenance.

However, a major disadvantage is that environmental issues central to society, such as biodiversity loss, disruption of natural processes, fragmentation of populations, erosion and stream sedimentation, loss of clean water, and reduction in fish populations, are marginalized. ISTEA, which funds improvements in transportation practices, permits but does not emphasize ecologically focused planning and practice. The challenge now is whether these central ecological issues can be effectively addressed by society within the framework of ISTEA. If not, a new framework is required to create an environmentally sustainable future, where human mobility and ecological patterns and processes are mutually benefitted.

A large portion of the contiguous United States, apparently well over 10%, is directly impacted ecologically by roads with vehicles. Minimizing road density in large natural-vegetation patches, including remote areas, is critical for maintaining our essential natural processes and richness of native plants and animals.

Roads and highways exist in the context of, and are strongly affected by, a broader landscape. The road also slices through and impacts many ecosystems and land uses within that land mosaic. Roads therefore must be planned, built and widened with a strong understanding of landscape and regional ecology. Indeed, because we know context is critical, it is both inadequate and unethical to not incorporate landscape patterns and processes squarely in the planning and construction process (Forman 1987). Planning for broad processes should reduce local species-by-species conflicts.

New road projects and retrofitting of roads built in the "pre-ecological era" should now incorporate wildlife-crossing mitigation structures, using the considerable European and some North American experience.

Public education, ecological research, and monitoring results of pilot projects should accompany this important step.

Environmental impact analyses are normally limited to specific projects and occur after decisions to build a road and the basic route are made. A new planning process is therefore needed, which focuses on the broad landscape, has ecology in its core, and elucidates route options long before a route is selected. A compatibility between an effective transportation system and robust ecological patterns and processes is attainable.

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