DRAFT

MEMORANDUM

Date: February 25, 2002

To: The Honorable Chair and Members
Pima County Board of Supervisors

From: C.H. Huckelberry
County Administrator

Re: **The Effects of Roads on Natural Resources**

The October 26, 2001 peer review of the work by the Science Technical Advisory Team recommended that the Sonoran Desert Conservation Plan give more attention to the effects of roads on wildlife and natural resources. The review stated in part that: "Roads are recognized by conservation biologists as a chief threat to many sensitive animals and to the general integrity of ecosystems. The Plan currently recommends maintaining certain percentages of vegetation cover in proximity to roads, which might be advantageous for some species (e.g., birds) but dangerous for others (e.g., large mammals, in that studies have shown that dense vegetation close to roads leads to increased collisions because of decreased visibility). Effective wildlife crossings as key points on high-volume roads should be recommended, important roadless areas and areas of low road density should be identified, and standards for minimizing road-building in high value habitats should be set."

Natasha Kline, a member of the Science Technical Advisory Team and biologist for Saguaro National Park, has undertaken a significant research effort about the impacts of roads on wildlife and the first of a two part study is attached. The study details the direct and indirect impacts of roads on natural resources, including direct mortality and loss of habitat, physical changes to the topography and hydrology of an area, impacts to habitat, noise, light and other types of pollution, and habitat fragmentation. The study notes that "particularly at risk from roadkill are populations of rare animals and long lived animals which naturally have high adult survival rates, usually combined with late maturity and low reproductive rates. These tend to be relative large animals, especially carnivores and certain reptiles. Local examples include Sonoran desert tortoise, gila monsters, mountain lions, black bears and badgers. ... Amphibians are another class of animals that have a life history pattern that makes them particularly vulnerable to roadkill ... [since] movements between wetland and upland areas often occur *en masse* during rainy weather conditions ... [and] migration routes are often intersected by roads; worse, amphibians may even be attracted to the puddles that form on roads and on the uneven road shoulder."

The attached primer will be followed by a study that includes specific data for Pima County impacts. On March 19, 2002 a forum will be held on the topic of the impact of roads. Recommendations to minimize the impacts of road-building in high value habitats will be forwarded to the Board.

Attachment

THE EFFECTS OF ROADS ON NATURAL RESOURCES

A PRIMER PREPARED FOR THE SONORAN DESERT CONSERVATION PLAN

by

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January 2002

EXECUTIVE SUMMARY

The purpose of this report is to describe the range of impacts that roads and road networks can have on wildlife and natural systems, and to identify roads as an issue relevant to the Sonoran Desert Conservation Plan (SDCP). About one-fifth of the U.S. landmass is directly affected ecologically by roads, and this number continues to rise. As scientific understanding of natural systems and their complexity and sensitivity has increased, biologists have documented many ways that motor vehicles, and the vast infrastructure needed to support them, have impacted and degraded the environment.

This report is intended to provide the reader with a general understanding of the scope of this issue by summarizing the many, interrelated mechanisms by which roads may impact the environment, the functions and processes of natural ecosystems, and ultimately the native plant and animal populations that the SDCP seeks to preserve.

The effects of roads on wildlife and natural systems are many, and cause impacts at various temporal and spatial scales. Some are direct effects (e.g., roadkill), and some are indirect (e.g., roads literally "pave the way" for increased human access and their subsequent activity and impacts). Some effects occur directly at the road site (e.g., changes to the topography of the road bed and surrounding area), while others occur off-site (e.g., mining materials for road construction). Many impacts occur in all of these ways (e.g., habitat loss, fragmentation and degradation). Cumulatively, the impacts from roadways are undeniably one of, if not, *the* biggest threat to wildlife and natural systems throughout the world today.

Creating roads causes direct and indirect mortality to plants and wildlife, destroys habitat, and physically disturbs the surrounding area. Once built, roads cause permanent environmental change in such parameters as: soil density, temperature, soil water content, light, dust, surface water flow, pattern of run-off, and sedimentation. These changes manifest themselves at varying distances from the road, some up to 100m. By altering the pattern, quantity and quality of both surface and sub-surface water/flow, roads often have profound impacts on area hydrology, which in turn may impact entire watersheds. Structures associated with roads also affect natural resources.

Chemical, particulate and noise pollutants account for another suite of impacts resulting from roads. Emissions occur from motor vehicles and road maintenance activities, as well as from the roads themselves. Numerous studies document the presence of pollution in biota inhabiting roadside edges, and virtually all measures of soil biotic diversity and function decline in such contaminated soil.

With an estimated one million animals killed on roads in the United States each day, roadkill is certainly the greatest, directly human-caused source of wildlife mortality throughout the United States. Particularly at risk from roadkill are populations of rare and/or long-lived animals that naturally have high adult survival rates, usually combined with late maturity and low reproductive rates. These attributes reduce their ability to withstand high or continuous adult mortality, which is characteristic of roadkill.

Far and away the biggest overall impacts that roads and road networks have on natural systems are the loss, degradation, and fragmentation of native habitats. When roads bisect or "fragment" habitat it affects animals at both the individual and the population level. Roads and other development surround and isolate individual animals, or populations of animals, and thereby reduce or prevent their natural movements and genetic exchange between their populations.

Roads facilitate human access into remote areas, as well as exotic plant and animal invasions. When a road is established, its cleared linear surface creates a new "edge" habitat with a different microclimate, with profound impacts on local plant and animal life. The species that benefit from these changes tend to be common and/or "weedy" species at the expense of locally endemic, highly specialized, and/or rarer species.

Roads are only one aspect of the development and urbanization that cumulatively poses the greatest threat to wildlife and natural systems in the world today. Like the effects of development, road impacts are cumulative and gestalt-like. Although it is often impossible to tease the specific effects of roads out of the overall impacts of development and urbanization, it is clear that roads affect, sometimes even wipe out, wildlife populations, and can irreparably damage whole natural systems and communities.

Many organizations provide information related to understanding and mitigating the effects of roads on natural resources and systems. An appendix of references for some of these organizations is provided in this report.

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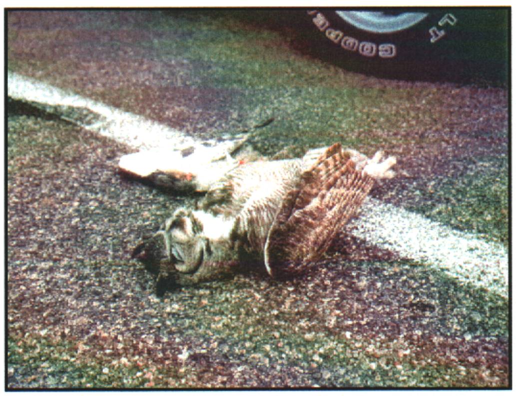
PURPOSE

The purpose of this report is to describe the range of impacts that roads and road networks pose to wildlife and to natural systems, and to identify roads as an issue relevant to the Sonoran Desert Conservation Plan (SDCP).

THE EFFECTS OF ROADS ON WILDLIFE AND NATURAL SYSTEMS

Animal-vehicle conflicts have been a conspicuous issue since automobiles rolled off the assembly line in the early 1900's; however, the impacts that cars had on wildlife were at that time generally regarded as insignificant (Robertson 1930, Howell 1934). For many years the central role that automobiles and roads would take in American society, and ultimately globally, and the cumulative, far-reaching effects they would have on all natural resources was unimaginable to most people. However, as our understanding of natural systems and their complexity and sensitivity increases, scientists have identified many ways that motor vehicles and the vast infrastructure needed to support them have impacted and degraded our environment. In the past twenty-five years, many of the effects that roads have on natural resources have been well documented throughout the world (Andrews 1990, Diamondback 1990, Bennett 1991, Forman and Alexander 1998, Spellerberg and Morrison 1998, Jackson 1999, Trombulak and Frissell 2000). However, quantifying these effects and teasing their significance out of the myriad of other impacts that human developments and urbanization have on the environment and wildlife populations is difficult (Trombulak and Frissell 2000), especially since some of the impacts may take years, even decades, to manifest themselves (Findlay and Bourdages 2000).

In 1934, A. Brazier Howell dismissed the potential for roadkill to become a serious problem for wildlife after noting that barnyard chickens had learned to avoid automobiles within some twenty years. He summarized, "I believe the average native bird to be fully the intellectual match of any domestic fowl, and that what the farmer has done the latter can do." Four years earlier, Robertson (1930) had also dismissed any significant impacts to bird populations resulting from motor vehicles when he declared, "... roadside mortality is only a minor factor, although a conspicuous one, in the avian reaction to the activities of man."



Studies have documented significant mortality from roadkill for several owl species (Loos and Kerlinger 1993, Baudvin 1997). Credit: NPS photo

The effects of roads on wildlife and natural systems are many, causing impacts at various temporal and spatial scales. Some are direct effects (e.g., roadkill), and some are indirect (e.g., roads literally "pave the way" for increased human access and subsequent activity and impacts). Some effects are primary, occurring at the site (e.g., changes to the topography of the road bed and surrounding area), while others are secondary, occurring off-site (e.g., mining materials for road construction). Many impacts occur at all four of these levels (e.g., habitat loss, fragmentation and degradation). With their cumulative impacts, roadways are undeniably one of, if not, *the* biggest threat to wildlife and natural systems throughout the world today.

The flow chart in Figure 1 illustrates some of the complex and interactive impacts to ecological systems resulting from the construction of roads and the resultant network ofroads, development and traffic. These pathways are all documented in the scientificliterature, although some are obvious (e.g., that direct wildlife mortality occurs from vehicular traffic on roads, and changes in a site's topography may change its hydrology, resulting in increased siltation). Following is an overview of the major categories of these impacts. It is intended to provide the reader with a general understanding of the scope of this issue by summarizing the many, interrelated mechanisms through which roads may impact the environment, the functions and processes of natural ecosystems, and ultimately the native plant and animal populations that the SDCP seeks to preserve.

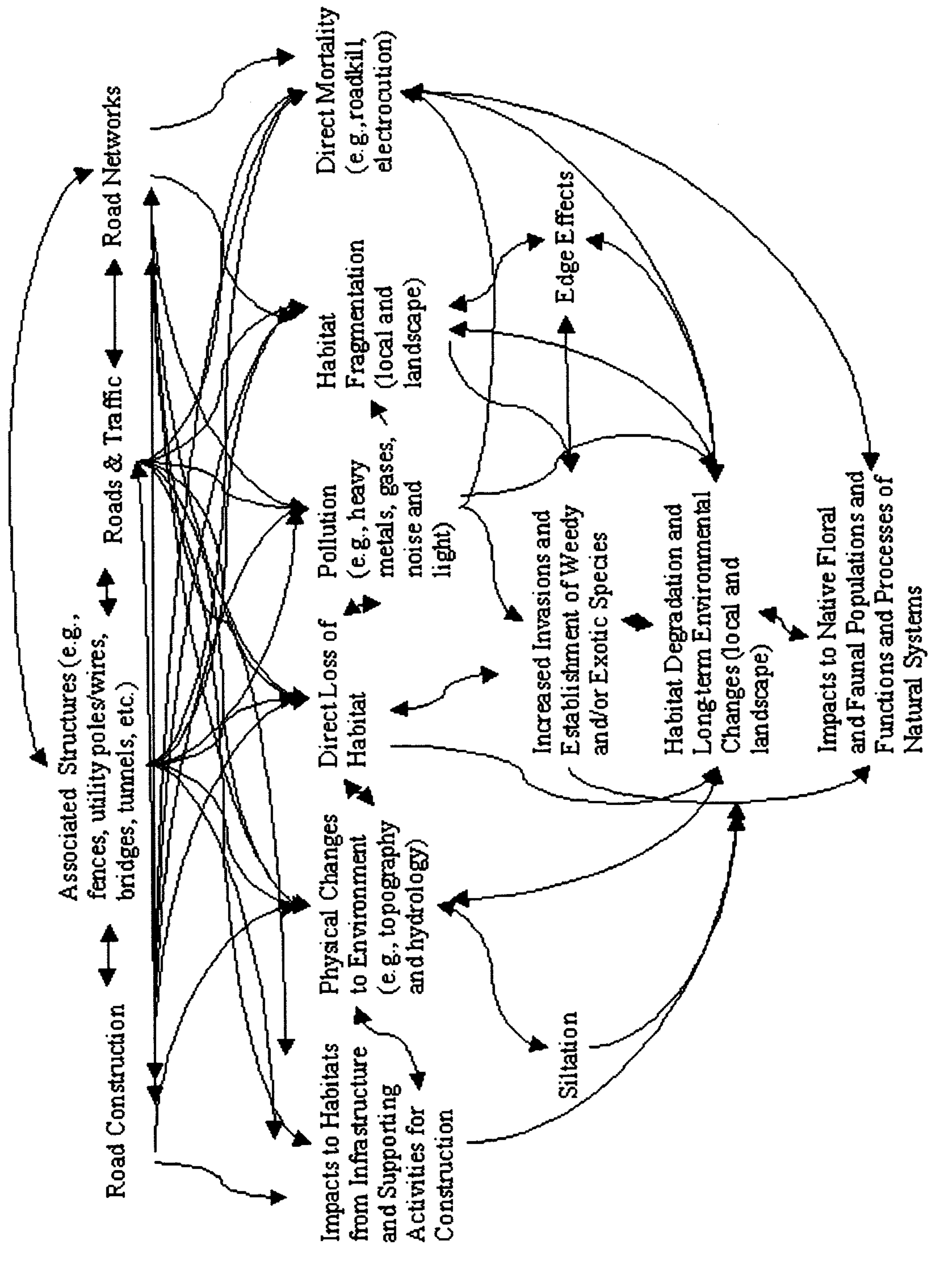


Figure 1. Flowchart of the interrelationships of the ecological effects of roadss.

I. ROAD CONSTRUCTION

Creating roads, whether by repeatedly driving a route to develop a two-track dirt road or constructing a four-lane interstate highway with heavy equipment, causes direct and indirect mortality to plants and wildlife, destroys habitat, and physically disturbs the surrounding area. The cumulative impacts of road construction activities in the United States are tremendous. In 1996 the U.S. Department of Transportation calculated that over 12 million acres of land and water bodies were destroyed by the construction of some eight million miles of roads, in addition to the plants, animals, and other organisms that inhabited those places (Trombulak and Frissell 2000). The actual figures are considerably larger since these impacts occur not only under the roadbed, but along the road shoulder, and also off-site, wherever fill or other roadbed and construction materials are mined, borrowed, stored or stockpiled (Spellerberg 1998, Trombulak and Frissell 2000). Forman (2000) calculates that about one-fifth of the U.S. landmass is directly affected ecologically by roads; and furthermore, that this number will continue to rise.

Road construction can dramatically change the topography of and around a roadbed, and the linear nature of roads tends to maximize this effect to impact a large scale. Disturbing, moving, and compacting soils for road construction results in: 1) the destruction of soil biota, plants, and sessile, slow-moving or dormant animals; 2) changes in surface and ground-water drainage patterns, which may either destroy or create wetland habitat; and 3) damaging erosion that often destabilizes the ecological integrity of the surrounding area and increases sedimentation (Diamondback 1990, Trombulak and Frissell 2000). Once a road is established, its cleared linear surface creates a new "edge" habitat with a different microclimate, which has profound impacts on local plant and animal life. All of these effects result in both immediate and longer-term impacts.

II. ENVIRONMENTAL CHANGE CAUSED BY ROADS

A. Terrestrial Environments

Once built, roads cause permanent environmental change. Trombulak and Frissell (2000) cite eight environmental parameters that are often altered by roads: soil density, temperature, soil water content, light, dust, surface water flow, pattern of run-off, and sedimentation. Soil density is greatly and permanently increased by road construction. This compaction causes decreases in soil biota (Riley 1984, Trombulak and Frissell 2000) and changes in subsurface water movement. The surface characteristics of roads (i.e., reduced water vapor transport, often darker color, and hardened, bare surface) increase their temperatures relative to the surrounding area, thus roads act as "heat islands." This often attracts animals to them. In forested areas, removal of trees for road construction allows for increased light penetration resulting in changes in plant species composition (Trombulak and Frissell 2000). Such changes in tree density and distribution also alters air movement through forests. Haskell (2000) cites this as the cause for significant decreases in leaf litter within 100m of roads in the southern Appalachian Mountains, which, in turn negatively affects the abundance and richness of macroinvertebrate soil fauna. Macroinvertebrates are a crucial factor in the soil's ability to process energy and nutrients; they also provide an important prey base for forest vertebrates such as salamanders and birds.

Dust and other particulates raised by motor vehicle activity coat vegetation and interfere with plant processes such as photosynthesis, transpiration and respiration. This effect can also alter plant community structure, especially lichens and mosses (Auerbach et al. 1997, Spellerberg and Morrison 1998). These changes manifest themselves at varying distances from the road, some up to 100m (Forman

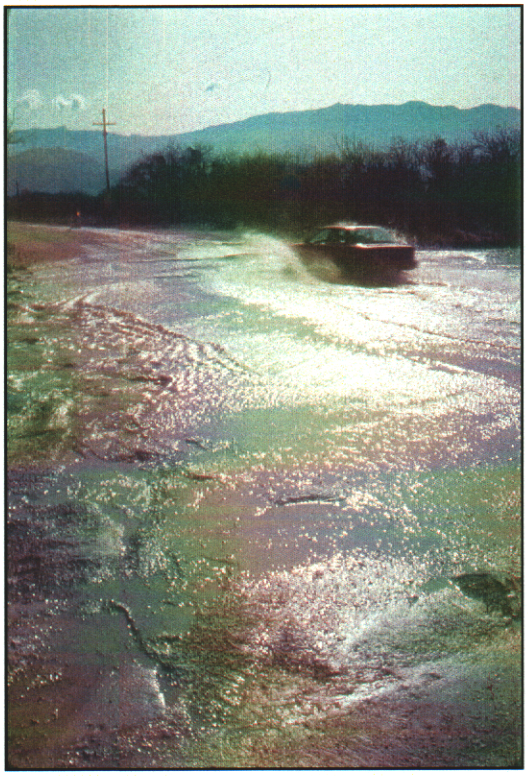
2000), and have implications for many ecological processes, and plant and animal species, at all different temporal and spatial scales.

B. Aquatic Environments and Hydrological Changes

Through altering the pattern, quantity and quality of both surface and sub-surface water/flow, roads often have profound impacts on area hydrology, which in turn may impact entire watersheds (Andrews 1990, Diamondback 1990, Ruediger and Ruediger 1999, Jones et al. 2000, Trombulak and Frissell 2000).

1. Surface Water Flow

The hydrology of streams and wetlands are directly impacted by roads. When they cross a stream, roads alter stream channels and change surface sheet flow patterns (Ruediger and Ruediger 1999, Trombulak and Frissell 2000). Roads can also act as dams, restricting the movements of fish and other aquatic vertebrates and the amount of water reaching downstream areas (Diamondback 1990); and they separate stream channels from their floodplains, making floodplains dysfunctional and affecting instream habitat (Ruediger and Ruediger 1999). The resulting alterations to surface-water habitats are often profoundly detrimental to native biota (Trombulak and Frissell 2000). In 1962 the U.S. Fish &Wildlife Service estimated that 99,292 acres of wetlands in Minnesota had been drained as a result of highway construction (Diamondback 1990).



In the desert southwest even urban roads frequently cross dry creek-beds or washes. During heavy rains, when these washes flow, the roads may flood and the surface water hydrology is altered. Credit: NPS photo

Roads increase the amount of impervious surface in a watershed thus increasing peak runoff and storm discharges (Diamondback 1990). When roads concentrate and increase surface water flows, they increase erosion. For example, erosion from logging roads in Idaho was 220 times greater than that at undisturbed sites (Diamondback 1990). The resulting channelization also increases sediment load, simplifies water current patterns, lowers the stream channel, drains adjacent wetlands, reduces the stability of banks, and increases downstream flooding (Trombulak and Frissell 2000). The effects of these changes may propagate long distances from the road site, and are unpredictable since they depend on flooding and sedimentation events which may occur long after the road is built (Trombulak and Frissell 2000). In fact, since such catastrophic responses are usually triggered by random, episodic events, such as infrequent intense rainstorms, years or decades may pass before the full effects of road construction are realized (Findlay and Bourdages 2000, Tromulak and Frissell 2000).

2. Sedimentation

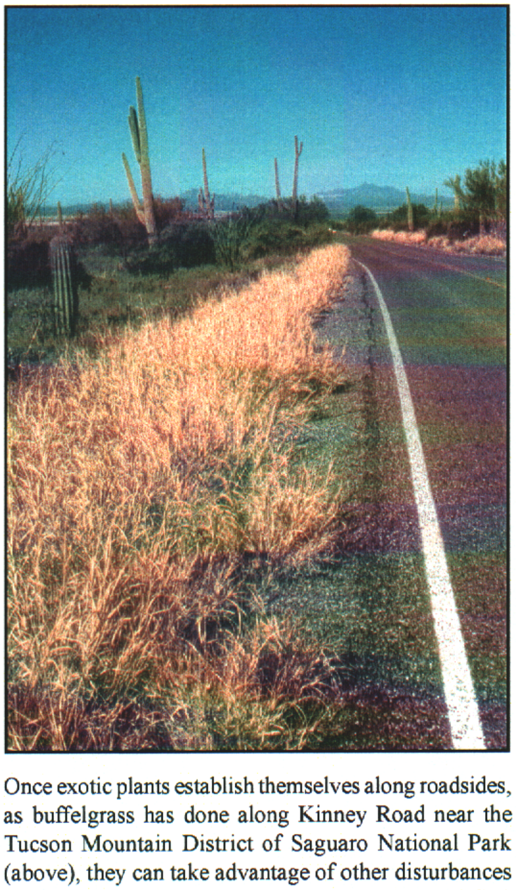
Roads greatly increase siltation of streams and other aquatic habitats. This mainly occurs through landslides and debris flows, which are dramatically increased with road building (Trombulak and Frissell 2000). In addition, chronic siltation from fine particles on roadways also occurs (Trombulak and Frissell 2000).

Increased sedimentation is known to be detrimental to fish, especially salmonids, because it decreases oxygen; it also negatively affects invertebrate numbers (Ruediger and Ruediger 1999, Trombulak and Frissell 2000). Andrews (1990) cited studies that documented highway construction that occurred in 11% of a watershed contributed to 85% of the sediment leaving the watershed, and that roads were the major source of increased sediment loads in other watersheds in which timber was harvested. This siltation caused a reduction in species diversity, reduction in biomass, and changes in plant species composition (Andrews 1990).

When rainfall flows off of paved roads it may either increase erosion and destabilize the roadside area, or create pools on roads and their shoulders, thus providing a resource that may draw animals to the road.

3. Subsurface Flows

Water tables are almost always lowered in the vicinity of a road (Andrews 1990). Through various means, roads intercept shallow groundwater flow paths and divert water along the roadway thereby efficiently re-routing it to surface water systems. This phenomenon often destroys and/or creates wetland habitats (Trombulak and Frissell 2000). These hydrological changes also increase streamflow rates and trigger erosion through channel downcutting, new gully or channel head initiation, and/or slumping and debris flows. Such events can create long-term negative impacts to vegetation, fishes and other biota far downstream (Andrews 1990, Trombulak and Frissell 2000).



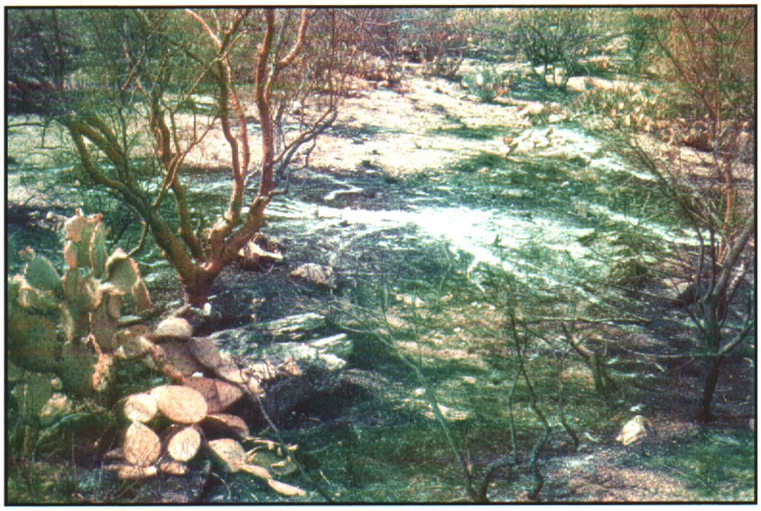
Once exotic plants establish themselves along roadsides, as buffelgrass has done along Kinney Road near the Tucson Mountain District of Saguaro National Park (above), they can take advantage of other disturbances (e.g., vehicle accidents or off-road activity, and fire) and invade the local plant community, often displacing the native species. Credits: National Park Service photo

III. EXOTIC SPECIES

Roads facilitate exotic species invasions and their subsequent establishment in a variety of ways. They act as corridors and dispersal agents for both plants and animals; they cause disturbance, changes in microhabitat, and create edge, thereby stressing native biota and providing suitable habitat for exotic species; and they act as reservoirs of seed sources (Parendes and Jones 2000, Trombulak and Frissell 2000). Cumulatively, these factors often tip the scales to favor invasive species over native ones. For example, Seabrook and Dettmann (1996) found that the introduced, toxic cane toad, which has deleterious effects on native Australian fauna, uses roads as activity and dispersal corridors to access and colonize new habitats.

When rainfall flows off of paved roads, it often makes the shoulder area wetter than the surrounding areas. Since these areas have usually been cleared of native vegetation, road shoulders provide prime habitat for the establishment of weedy exotic plants and become corridors for exotic plant invasions, especially when motor vehicles disperse their seeds. A local example is buffelgrass *(Pennisetum ciliare)*, a very aggressive South African bunch grass, which has become established in Arizona and is prominent around Tucson. Similarly, maritime plants become established in inland environments where deicing salts are used on roads (Trombulak and Frissell 2000).

Fire is one of the mechanisms bufflegrass exploits to invade new areas (McAuliffe 1995). Exotic grasses along roadsides are relatively lush and contiguous—the perfect fuel for starting a fire from a cigarette carelessly tossed out of a car. The Sonoran desert is not a fire-adapted ecosystem. Fires, especially if they are fueled by exotic grasses, burn hotter, more frequently, and spread farther than any otherwise might, and often kill mature native desert vegetation. The openings created by the loss of vegetation from fires further facilitate the invasion of exotic plants, and a cycle of replacing native plants with exotic ones may begin (D'Antonio and Vitousek 1992).



Palo verde trees and cactus, specifically saguaros, are particularly vulnerable to fire damage (McLaughlin and Bowers 1982, Rogers 1985). Credit: NPS photo

Traditionally, landscape architects took advantage of the invasive qualities of exotic plants and often used them for erosion control along roadsides (Trombulak and Frissell 2000). This practice is less common today, given the ecological ramifications; however, exotic species are still preferred by some landowners and landscapers (Dunlap 1987).

Roads that run through or near aquatic environments also create easy access for humans to initiate legal and illegal introductions of fish, turtles, crustaceans, mollusks, plants and other aquatic organisms, which may have many disruptive and detrimental impacts to native aquatic ecosystems (Trombulak and Frissell 2000). These effects can be insidious, yet have major consequences to ecosystems. For example, Port Orford cedars, which are a keystone species in northwestern riparian ecosystems, are now threatened from an exotic root disease. Spores from the fungus *Phythoptera lateralis* are transported by vehicles on logging and mining roads into headwater stream crossings. The water-borne spores then invade large portions of the watershed, killing even trees deep in roadless areas. The long term consequences of this process are expected to be far-reaching and dramatic for the forest ecosystem (Trombulak and Frissell 2000).

IV. ASSOCIATED STRUCTURES

Structures associated with roads also affect natural resources. Fences and retaining walls may create impassable barriers for terrestrial and aquatic animals. Utility towers and wires cause collisions with and electrocutions of birds (Robertson 1930, Stout and Cornwell 1976, Avery et al. 1980, Andrews 1990), and there is some concern that the powerful electromagnetic fields generated by high voltage power lines may have harmful effects on humans and wildlife (Dawson et al. 1998, Fear and Stuchly 1998). Bridges and culverts affect the hydrodynamics and sedimentation of the waterways they span, alter surface-water habitats (Trombulak and Frissell 2000), and restrict passage of fish (Diamondback 1990). Rest areas concentrate human activity along roads causing disturbance and habitat destruction to many species (Trombulak and Frissell 2000). Signs and lights may cause disorienting light pollution (Cochran and Graber 1958, Verheijen 1958, McFarlane 1963) and affect the activity periods of birds and frogs and the growth patterns of plants (Forman and Alexander 1998, Spellerberg 1998).

V. POLLUTION

Pollutants account for another suite of impacts resulting from roads. Emissions occur from motor vehicles and road maintenance activities, as well as from the roads themselves. There is more literature on the chemical effects of roads on the environment than for any other road impact (Spellerberg 1998, Trombulak and Frissell 2000). Numerous studies document the presence of pollution in biota inhabiting roadside edges, but few papers discuss the effects of these substances (Spellerberg and Morrison 1998, Trombulak and Frissell 2000). Hellawell (1988) noted that few generalizations could be made about the effects of potential pollutants on biota because different species of plants and animals tend to respond to different pollutants in different ways, even at different stages in their life histories.

A. Chemical

Generally, there are five classes of chemicals that roads contribute to the environment – heavy metals, organic pollutants, ozone, deicing salts, and nutrients.

1. Heavy Metals

Heavy metals, specifically lead, aluminum, copper, zinc, cadmium, manganese, titanium, nickel, chromium and boron, are gasoline additives that accumulate in soils and plant and animal tissues in a gradient that decreases exponentially away from the road. These gradients are also influenced by prevailing winds (Broadbent and Cranwell 1979, Spellerberg 1998, Trombulak and Frissell 2000). Above background traces of heavy metals have been recorded in plants up to 150m from roads (Spellerberg 1998). These compounds subside in the soil but are also readily transported in and by aquatic environments. Thus, although levels of heavy metals are known to decrease in areas where leaded gasolines are no longer used, they do not disappear. Rather, they move through the soil eventually ending up in aquatic environments (Trombulak and Frissell 2000).

2. Organic Pollutants

Organic pollutants (e.g., dioxins and polychlorinated biphenyls) are also found in higher concentrations along roadsides (Trombulak and Frissell 2000), and hydrocarbons may accumulate in aquatic ecosystems near roads.

3. Ozone

Ozone is a harmful gaseous molecule produced by vehicles as a by-product of gasoline combustion. Ozone and nitrogen oxides are well known to have damaging effects on certain plant communities, and to water and air quality (Jacobsen and Hill 1970, Sandermann et al. 1996, Miller et al. 2000).

4. Deicing Salts

Deicing salts alter soil pH and chemistry and affect aquatic environments, thereby causing plant damage and changes to plant and aquatic communities (Spellerberg and Morrison 1998). Salts may also attract animals, especially mammals, to roadsides, thus making them more vulnerable to roadkill.

5. Nutrients

Roads dump nutrients (i.e., nitrogens and phosphorous from nitrous oxide, particulates, and deicing salts) directly into the environment, bypassing the natural pathways which would normally buffer these compounds (Trombulak and Frissell 2000). Increased nitrogen levels along roadsides may significantly increase plant growth rates up to 200m away from roadsides, thereby affecting species composition (Spellerberg 1998).

6. Overall Effects of Pollutants on Biota

Virtually all measures of soil biotic diversity and function decline in contaminated soil, including abundance, number of species, and species composition (Trombulak and Frissell 2000). Pollutants also affect plant health by damaging fine roots, mycorrhizae and leaves, and by changing salt concentrations in plant tissues; they also reduce plants' resistance to pathogens. Plants begin to defend themselves against these environmental insults at the expense of their normal life functions, and eventually growth and the overall health of plants can be depressed, even to the point of death (Trombulak and Frissell 2000).

Plants and animals that live or forage along roadsides (including those raised for consumption) may accumulate toxin levels that pose health hazards (Spellerberg 1998, Trombulak and Frissell 2000).

B. Particulates

Particulates on road surfaces become airborne from vehicle activity or wind. These particles affect air quality and visibility. When these particles resettle on plants they may affect photosynthesis, respiration and transpiration, and facilitate the effects of gaseous pollutants such as nitrous oxide and ozone. Lichens and mosses are most sensitive to these effects (Spellerberg 1998).

C. Litter

Discarded trash, especially food and/or food containers, attracts animals to the road where they are more likely to be hit by cars. It also may poison or malnourish them. Litter and trash may also entangle and/or strangle wildlife, and discarded bottles trap many small mammals (Andrews 1990). In fact, sampling such litter has been used in some areas as a method for surveying small mammals (Pagels and French 1987)!

D. Noise

Traffic noise is a conspicuous by-product of roads and road networks. Forman and Alexander (1998) cited noise as the most important aspect of traffic disturbance that caused animals to avoid roads. They believed this to be a much greater overall impact to wildlife than roadkill. Forman and Deblinger (2000) point out that noise effects, unlike some other impacts from roads, exert effects along virtually the entire length of the highway they studied. Research in the Netherlands identified noise as *the* significant parameter causing reduced densities of nesting birds near roads (Reijnen et al. 1995, Reijnen et al. 1996). The cause of this phenomenon is thought to be a combination of overall stress from noise and interference with intraspecies communication (Reijnen et al. 1995). Behavioral changes in and negative impacts to wildlife from vehicle noise have also been documented in other wildlife species (Brattstrom and Bondello 1983, Andrews 1990, Forman and Alexander 1998).

VI. ACCESS

Perhaps the biggest negative effect of all from roads on wildlife and natural systems is that one road, even a dirt one, increases the likelihood of further invasion and impact by humans, more development, and so on. Roads today function much like the railroads of the "old west." Just as with exotic plants and animals, roads facilitate human access into formerly remote areas, and increase the efficiency with which natural resources can be extracted. This is especially true with commercial activities, but is also true for private ventures. To quote Trombulak and Frissell (2000), "Roads are often built into areas to promote logging, agriculture, mining, and development of homes or industrial or commercial projects. Such changes in land cover and land and water use result in major and persistent adverse effects on the native flora and fauna of terrestrial and freshwater ecosystems."

Roads also facilitate illegal activities, such as poaching and arson, as well as legitimate access to areas for hunting, fishing and recreation. Even seemingly benign activities like hiking, camping or birding create passive disturbance to animals, and increase the likelihood of habitat altering events such as fire and the (intentional or unintentional) introductions of exotic plants and animals (Trombulak and Frissell 2000).

Roads in desert environments, even when abandoned and closed, remain visible for decades. The characteristic low rainfall, high temperatures and unproductive soils of these climates make natural recovery of desert vegetation a very slow process. These roads remain attractive nuisances for continued traffic, which further impedes the recovery process.

VII. ROADKILL

An estimated one million animals are killed on roads in the United States each day (Forman and Alexander 1998). Roadkill is certainly the greatest, directly human-caused source of wildlife mortality throughout the United States, but is also one of the least understood. Although the many impacts of roads on wildlife and natural systems are well documented, few formal studies have been conducted specifically to examine the effects of road mortality on wildlife populations in an area (Kline and Swann 1998). In fact, roadkill is often assumed not to impact wildlife at the population level (Adams and Geis 1983, Reijnen et al. 1995, Forman and Alexander 1998, Spellerberg 1998). However, at least for some species there is clear evidence that road mortality can be significant at the population level (Diamondback 1990, Ruediger 1996).

Roads provide easy access to backcountry areas where natural resources may be disturbed or destroyed. Credit: Don Swann

Particularly at risk from roadkill are populations of rare animals (i.e., animals that naturally occur in low densities or that occur in low densities due to anthropogenic factors), and/or long-lived animals which naturally have high adult survival rates, usually combined with late maturity and low reproductive rates. These tend to be relatively large animals, especially carnivores and certain reptiles (Fowle 1996, Boarman et al. 1997, Ruediger and Ruediger 1999). Local examples include Sonoran desert tortoise, gila monsters, mountain lions, black bear and badgers. For these species, survival of adults and juveniles is often a bigger factor in maintaining population stability than fecundity, nest survival (for reptiles) or age at sexual maturity (Fowle 1996). These attributes reduce their ability to withstand high or continuous adult mortality, which is characteristic of roadkill. Once impacted, recovery for these populations is also slow.

Amphibians are another class of animals that have a life history pattern that makes them particularly vulnerable to roadkill (Trombulak and Frissell 2000). Many toads, frogs and salamanders spend portions, if not all, of their adult lives in upland areas, yet they must always return to wetlands to breed and lay eggs. These movements between wetland and upland areas often occur *en masse* during rainy weather conditions when all the adults emerge to take advantage of a short window of opportunity to locate a pond or pool of water, find a mate and lay their eggs. These migration routes are often inter-

In some areas bobcat populations are threatened by roads, specifically by habitat changes and increased access by hunters and trappers; roadkill may also be a factor (Lovallo and Anderson 1996). Credit: Bobbi Simpson

Bill Ruediger, a Forest Service biologist studying the impacts of roads on large carnivores, noted that with their very large home ranges, large carnivores in the U. S. end up crossing not one, but many highways in order to fulfill their biological needs (Ruediger 1996). He further contends that, "At some point, large carnivores cannot compensate for the increased mortality, and the combined impacts of habitat fragmentation, displacement and avoidance, habitat loss and associated human development, overwhelm a species .... This has occurred for most large carnivores over much of the United States."

In Australia, cassowaries, a large ostrich-like bird, are attracted to roads by people feeding them and then often become roadkills. Credit: Don Swann

Colorado River toad populations may be locally threatened by roads. Credit: © Cecil Schwalbe

Although it tends to be the large charismatic megafauna that we see on roadsides and that causes our concern, some of the smallest animals are the most significantly impacted by roadkill. Locally, certain amphibians, like the Colorado River toad, may be inordinately affected by roads. These toads' breeding or dispersal movements for an entire year may occur in one or two nights after a key summer rain. If the toads have to cross a road to reach a puddle to breed in, or worse yet, are attracted to puddles on the road itself, toad carnage ensues. This problem has been identified in many other places throughout the world (Langton 1989, Trombulak and Frissell 2000). In some instances it has been successfully mitigated with "toad tunnels," which provide safe passage for toads and other amphibians across a road (Langton 1989).

sected by roads; worse, amphibians may even be attracted to the puddles that form on roads and/or on the uneven road shoulder. Once on the road, their numbers, inconspicuousness, and relative slowness make them inevitable victims of vehicles. Such massacres have been shown to threaten local populations (Reh and Seitz 1990) and have been documented throughout the world (Trombulak and Frissell 2000).

Documented examples of animal populations affected by roadkill include: Mexican rosy boas (in Organ Pipe Cactus National Monument in Arizona; Rosen and Lowe 1994), black bears (it is estimated that 9-11% of the black bear population is killed yearly on highways and railways in Banff National Park in Canada; Gibeau and Heuer 1996, Ruediger 1996), Mojave desert tortoises (Boarman et al. 1997), painted turtles (Fowle 1996), timber rattlesnakes (Rudolph et al. 1998), and common frogs (Reh and Seitz 1990). Roadkill is also the primary cause of mortality and is limiting the ability to recover several endangered species, including the American crocodile, Florida panther, Florida black bear, and key deer (Trombulak and Frissell 2000). In conjunction with habitat loss and fragmentation, roadkill can also cause local extinctions in refuges or parks too small to sustain the highway losses relative to the replacement rates (Pressey et al. 1981).

VIII. ROAD CHARACTERISTICS, TRAFFIC, AND ANIMAL BEHAVIOR

It is intuitive that an interstate highway will have greater impacts on natural resources and systems than a backcountry dirt road. All of the potential impacts to habitat and the environment described already (above) are scaled up. Four factors influence wildlife mortality on roads – the amount, pattern, and speed of traffic on a road, and the location of the road in relation to animal habitat and movements. Usually the first three characteristics are closely correlated to each other and to road condition/characteristics. Generally, roads with the most use warrant the expense of improvement, and the better maintained the road, the faster cars will go on it, resulting in more roadkills. If a road runs through high quality wildlife habitat, or crosses wildlife movement corridors, the potential for vehicle/wildlife conflict increases. Forman and Alexander (1998) concluded that amphibians and reptiles tend to be killed in large numbers on two lane roads with low to moderate traffic; large and mid-sized mammals on two lane high-speed roads; and birds and small mammals on wider, high-speed highways. Note that over time a given road may fit all of these categories, thus maximizing the cumulative mortality on all taxa.

Roads, even small (less than 3m wide) dirt roads, are well documented as barriers for wildlife movements, especially for small mammals and invertebrates (Andrews 1990).

The barrier may be a physical one (such as for reptiles which may not be able to negotiate a curb or other roadside structure), a psychological one (such as for pronghorn; Van Riper and Ockenfels 1998), or a functional one (where animals may attempt to cross, but never make it, generally due to roadkill).

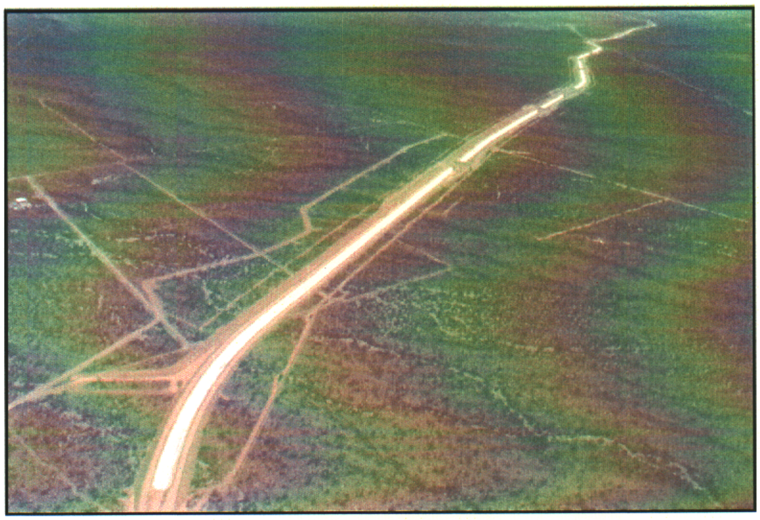
The presence of a road may affect an animal's behavior in many ways. Trombulak and Frissell (2000) identify and provide examples of five behavioral mechanisms through which animals may respond to roads – shifting their home range, altering their movement patterns, altering their reproductive success, altering their escape response, or altering their physiological state. These indirect impacts can be just as detrimental to wildlife populations as the direct effect of roadkill. Thus, ironically, avoiding roads can be just as potentially dangerous to animals as crossing roads. For example, if a road bisects an animal's territory or home range so that it avoids the road and will not cross it, then the road has effectively eliminated resources that animal needs. So roads break up, or fragment, and thereby reduce, habitat. This "habitat fragmentation" effect impacts animals at both the individual and the population level.

Roads and other development surround and isolate individual animals, or populations of animals, and thereby reduce or prevent their natural movements and genetic exchange between their populations. This phenomenon has been quantified by two German scientists who documented reduced genetic variability in a population of common frogs that was isolated from other common frog populations by roads and railways (Reh and Seitz 1990). For many reasons, isolated populations are much more prone to extinction than those that allow immigration from surrounding populations.

IX. ROAD NETWORKS

A. Habitat Fragmentation

The negative impacts that roads have on natural systems greatly increase with road density. Far and away the biggest overall impact that roads and road networks have on natural systems are the loss, degradation, and fragmentation of native habitats (Spellerberg and Morrison 1998). In this way roads are simply one component of the development and urbanization that cumulatively pose the greatest threat to wildlife and natural systems in the world today, and have implications for loss of biological diversity at the species, population and genetic levels (Spellerberg and Morrison 1998). Habitat loss and changes are the bottleneck where all of the potential negative effects from roads and development come together to impact plants and animals at the population level, as well as to disrupt crucial natural processes.



In the Tucson Basin, urban sprawl, including roads, and large scale developments like interstate highways and the Central Arizona Project, causes habitat loss and fragmentation which threaten local wildlife and natural systems. Credit: NPS photo

In the Rocky Mountains, roads contribute more to forest fragmentation than clearcuts (Spellerberg and Morrison 1998). When roads cut through otherwise undeveloped areas they fragment the larger area and create edge. Both of these results have profound negative effects on the integrity of the native ecosystem and the ability of animals to move around and access the resources they need to survive. Spellerberg and Morrison (1998) note, "Habitat fragmentation results in loss of habitat, an increase in the numbers of fragments, and the isolation of populations (which has implications for loss of biological diversity at the population and genetic level). For some taxa, the area of habitat becomes too small to support the resources needed for survival." Depending on the size of the animal a road may physically separate animals into discrete populations. Roads may reduce the size of an individual animals' territory, perhaps excluding certain, necessary resources so that the fragmented habitat is much reduced in quality, or no longer viable habitat at all. A road doesn't just divide the existing environment into two intact parts, it creates an ecologically arbitrary boundary that disrupts animal movements and access to crucial habitats and resources (i.e., home ranges, summer and winter ranges, water, mineral licks, escape routes, wetland breeding sites for amphibians, and upland nesting sites and hibernacula for turtles and snakes; Jackson and Griffin 1998, Trombulak and Frissell 2000). Creating smaller fragments of habitat also has implications for ecological processes and reduces the resilience of communities to recover from perturbations (Spellerberg and Morrison 1998).

B. Edge

Roads also create new "edge" habitat, which further serves to fragment the native matrix environment, and provides a corridor for invasions by predators and competitors (i.e., exotics and weedy, habitat generalists). Edge is a human artifact created by clearing native vegetation and causing two contrasting habitats (the native and the cleared) to suddenly converge without natural gradations. Edges experience a different microclimate, which in turn effects a change in community (Andrews 1990, Spellerberg 1998). If habitats are fragmented too much and the ratio of edge to interior favors edges, that habitat will no longer be suitable for the more specialized interior species that generally are the most threatened. "Weedy" species with good dispersal capabilities typically invade and colonize disturbed habitats. They are attracted to edges and can move into previously undisturbed habitat when a road or utility corridor provides that opportunity.

C. Exotic/Weedy Species Invasions

The railroads built across the western United States in the 1860s only directly impacted a tiny fraction of the land, but they fragmented the landscape and allowed for the invasion of settlers, who could then, from this thin metal corridor, exert major ecological changes on the landscape. Similarly, even narrow roads through forested areas can result in edge effects that can have negative consequences for the function and diversity of the ecosystem (Haskell 2000). In the Amazon, interior forest birds avoid edge more than 50m into the forest, and an "edge species" of butterfly will invade 200-300m into the forest (Lovejoy et al. 1986). Rich et al. (1994) blame modern declines in American forest birds on forest fragmentation after noting that even a narrow corridor through the forest significantly affected the distribution and abundance of birds.

X. POTENTIAL POSITIVE EFFECTS OF ROADS

Some wildlife species do benefit from certain aspects of road development. In fact, an entire roadside ecology develops around a new road. For example, though they risk getting hit by a car while foraging there, scavengers may benefit from increased food found along roadsides; birds feed on grit provided along roadsides; and bridges and tunnels may create habitat, nesting, and roosting areas for some birds and bats (Carey 1998, Keely and Tuttle 1999, Wolf in prep.). Roads also seem to facilitate range extensions in some species (Huey 1941, Getz et al. 1978), or at least provide travel corridors, especially on plowed roads in the winter (e.g., bison in Yellowstone National Park). However, the species that benefit from these developments tend to be common and/or "weedy" species (widespread, generalist species that excel at exploiting disturbed habitats) at the expense of locally endemic, highly specialized, and/or rarer species. This homogenization, in which locally endemic or rare species are replaced with common generalist species, ultimately decreases biodiversity, both locally and globally. In fact, this phenomenon is not unlike human cultural globalization. Today in major cities throughout the world European house sparrows forage for crumbs at McDonald's restaurants. Ultimately, the competitive advantage of each (behaviorally in the case of the sparrow, and economically in terms of the McDonalds) has a dilution effect on the local endemism of the area, one biologically and one culturally.

Structures associated with roads may provide habitat for wildlife, but can often end up killing them too. For example, utility poles provide perches for raptors, but may also electrocute them. Snakes and other reptiles often use the flat warm surfaces of roads for basking, but are frequently killed on them by cars.

Overall, the detrimental effects of roads by far outweigh any advantages to wildlife, both in the short-term and particularly the long-term (Spellerberg and Morrison 1998).

XI. OVERALL EFFECTS OF ROADS AND ROAD NETWORKS ON NATURAL RESOURCES AND SYSTEMS

Road impacts are cumulative and gestalt-like. Although it is impossible to tease the specific effects of roads out of the overall impacts of development and urbanization in general, it is clear that cumulatively roads affect, sometimes even wipe out, wildlife populations, and can irreparably damage whole natural systems and communities.

Table 1 (from Schoenwald-Cox and Buechner 1992) provides a summary outline of the effects of fragmentation, specifically that caused by roads, on a landscape and the natural systems and wildlife on it.

At the landscape scale the major ecological impacts of a road network are the disruption of landscape processes (i.e., "horizontal" natural processes, like groundwater and stream flow, fire spread, foraging and dispersal) and loss of biodiversity. Roads may truncate flows and movement, thereby reducing critical variability in natural processes and disturbances. Trombulak and Frissell (2000) coin the term "hyperfragmentation" to describe the far-reaching ecological effects that occur with road networks. Forman and Deblinger (2000) calculated that *all* of the nine ecological factors they measured along roadsides had impacts that extended at least 100m from the road, with some extending outwards of 1km. Forman and Alexander (1998) estimated that 15-20% of the United States was directly affected by roads. Figure 2 shows the primary and secondary highways in the United States. Given the extent of these roads and their influence, it is clear that roads have dramatically altered the ecology of North America. These impacts of course, are increased and confounded by other human development and urbanization.

The mechanism of wildlife population loss by roads is summarized in Findlay and Bourdages (2000) as follows.

> Road construction may result in significant loss of biodiversity at both local and regional scales due to restricted movements between populations, increased mortality, habitat fragmentation and edge effects, invasion by exotic species, or increased human access to wildlife habitats, all of which are expected to increase extinction rates or decrease local recolonization rates. Species loss is unlikely to occur immediately, however. Rather, populations of susceptible species are expected to decline gradually after road construction, with local extinction occurring sometime later.

Indeed, this is what we see locally. When was the last time you saw a gila monster in your backyard?

TABLE 1. SUMMARY OF SOME MAJOR EFFECTS OF LANDSCAPE FRAGMENTATION ON SENSITIVE SPECIES OR SYSTEMS, PARTICULARLY AS DETERMINED BY ROADS WITHIN PARKS.

(from Schoenwald-Cox & Buechner 1992)

I. Modification of Habitat
- A. Changes in the size and shape of landscape elements
  1. Decreased size of continuous habitat in remnant patches
  2. Altered shape of continuous areas of patch interior habitats
  3. Altered geometry of edges
  4. Increased perimeter:area ratios of remnant patches
- B. Changes in the connectivity and isolation of landscape elements
  1. Increased degree of isolation of remnant patches for species, materials or effects restricted to patch interior habitats
  2. Increased connectivity of remnant patches for species, materials, or effects following edge or modified habitats.
  3. Increased access for logging, mining, hunting and other resource-extraction activities.
  4. Increased access for poachers and other illegal activities
- C. Changes in habitat types
  1. Increased amount of edge and modified habitat
  2. Decreased amount of patch interior habitats
  3. Changes in the composition and geometry of edge habitats
  4. Loss of sensitive species from small remnant patches
  5. Altered balance of exotic and native species
  6. Altered balance of weedy or edge and patch interior species
  7. Increased spatial and temporal variation in habitat quality for patch interior species
  8. Increased habitat homogeneity within small remnant patches
  9. Changes in the capacity of the reserve for populations of sensitive species

II. Modification of the quality of protection provided
- A. Changes in balance of patch interior versus edge species and native versus exotic species
- B. Increased exposure of internal areas and further subdivision of landscape
  1. Direct removal of habitat
  2. Increased amount of edge in landscape
  3. Increased exposure to edge effects
  4. Increasing fluctuation of microclimate and related processes
  5. Influx of foreign materials (pollen, insects, toxins, garbage, etc.)
  6. Disturbance of habitat (soil compaction, direct destruction of vegetation or substrate, etc.)
- C. Declines of populations of species that:
  1. Occur naturally at low densities
  2. Have large area requirements
  3. Do not do well in edge habitats
  4. Are sensitive to human contact
  5. Are unlikely or unable to cross roads
  6. Are frequently killed on roads (e.g., seek out roads for food or heat)
  7. Are otherwise sensitive to extinction resulting from habitat fragmentation or disturbance

III. Major Observed Changes
- A. Peninsula effects and some island effects
- B. Altered population dynamics of many species
- C. Possible increased probability of further fragmentation
- D. Increase in absolute amount of edge in the landscape
- E. Decrease in the amount of edge that can support sensitive species
- F. Subdivision of protected habitats and forced metapopulation structure of patch interior species
- G. Altered patch dynamics; for example, loss of species for which patch colonization rates are lower than local patch extinction rates
- H. Increased instability of ecological processes and increased frequency of fluctuation in habitat quality
- I. Predisposition of local extinction of some species

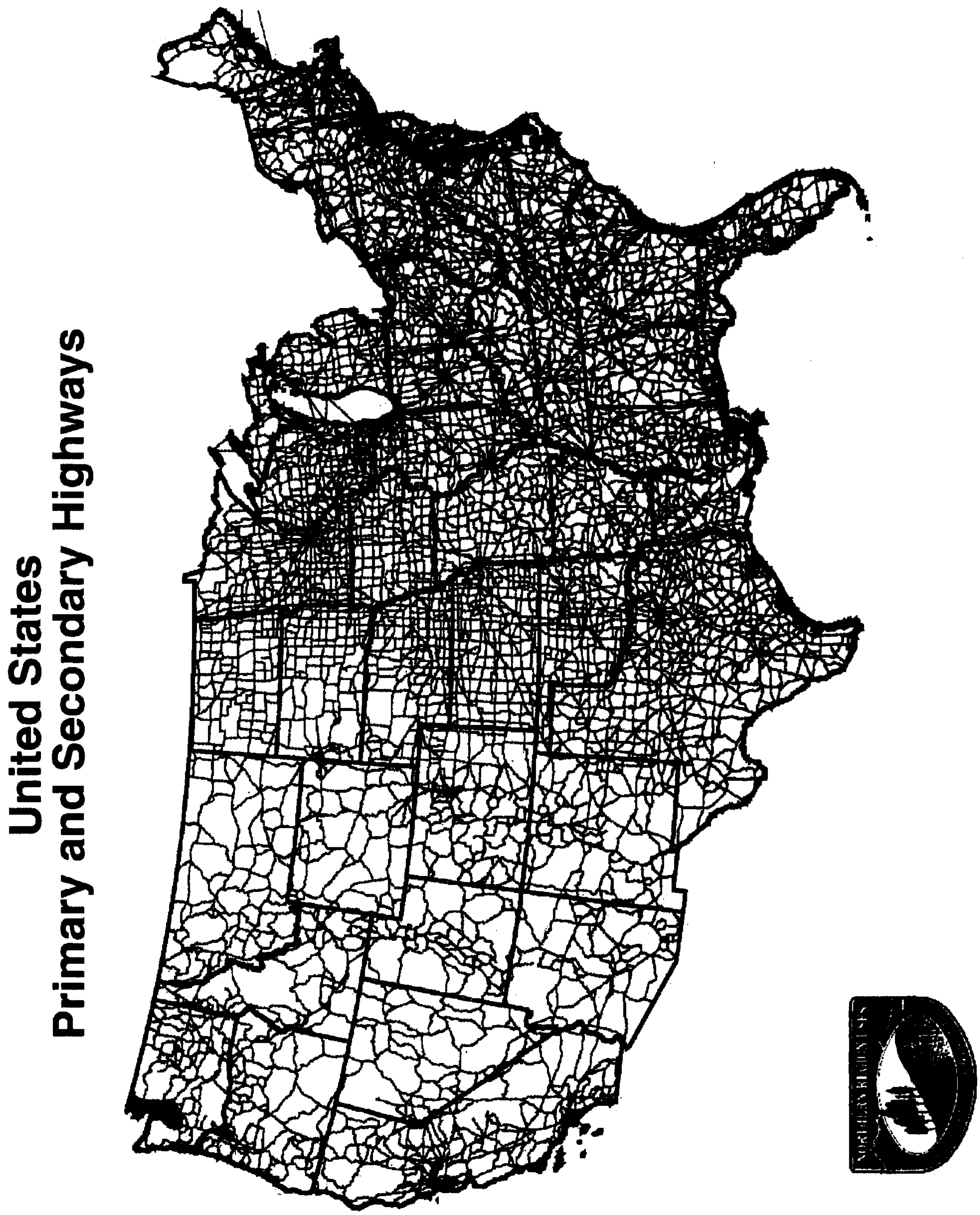


Figure 2. Primary and secondary highways of the United States (U.S. Forest Service map, from Ruediger 1998).

ACKNOWLEDGMENTS

Frank Walker and Meg Weesner have supported studies on the effects of roads on park resources in Saguaro National Park, as well as my involvement with the Sonoran Desert Conservation Plan. Don Swann, Laura McMahon, Martin Pokorny, Adrian Schaefer, Mike Ward, Tiffany Volz, Kristen Beupre, and many, many other park staff and volunteers have contributed to the park's and my understanding of the effects of roads on natural resources, particularly wildlife. Maeveen Behan, Julia Fonseca, Christine McVie, Carolyn Campbell, and Trevor Hare greatly inspired me to contribute this work to the Sonoran Desert Conservation Plan. Bobbi Simpson, Cecil Schwalbe, and Don Swann generously donated photos for use in this report. I thank them all.

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APPENDIX A

(Related Organizations and Resources)

APPENDIX A. RELATED ORGANIZATIONS AND RESOURCES

Banff National Park's website includes information on their landscape scale highway mitigation project.
HtmlResAnchor http://www.worldweb.com/ParksCanada-Banff/Roads

Center for Transportation and the Environment (CTE) is a U.S. Department of Transportation University Transportation Center (UTC) located at North Carolina State University. It is the only UTC in the country that seeks to mitigate the impacts of surface transportation on the environment.
HtmlResAnchor http://www.itre.ncsu.edu/cte/cte.html

Critter Crossings: Linking Habitats and Reducing Roadkill is the Florida Department of Transportation's website that describes the impacts of transportation on wildlife and highlights exemplary projects and processes that are helping reduce these impacts.
HtmlResAnchor http://www.fhwa.dot.gov/environment/wildlifecrossings

Defenders of Wildlife Habitat & Highways Campaign The mission of this campaign is to reduce the impact of surface transportation on wildlife and habitat and to incorporate wildlife conservation into transportation planning.
HtmlResAnchor http://www.defenders.org/habitat/highways

Environmental Defense focuses on the best, most equitable way for America to get from here to there without harming the environment.
HtmlResAnchor http://www.environmentaldefense.org/programs/transportation

Fatal Light Awareness Program (FLAP) is working to preserve the lives of migratory birds in urban areas.
HtmlResAnchor http://www.flap.org

Friends of the Earth (FOE) works with conservative taxpayer groups and community activists across the nation to oppose many unneeded and unwise roadways.
HtmlResAnchor http://www.foe.org/ptp/sprawl/roadtosprawl/foe.html

Infra Eco Network Europe (IENE) is a European network of experts and institutions involved in the field of habitat fragmentation and transportation infrastructure.
HtmlResAnchor http://iene.instnat.be/right.html

National Wildlife Federation: Smart Growth and Wildlife Campaign is working across the US to protect and restore species and habitats threatened by sprawl, promoting "smart growth" alternatives.
HtmlResAnchor http://www.nwf.org/smartgrowth

Natural Resources Defense Council: Smart Growth is working toward smart-growth solutions that can help curtail sprawl and build more sustainable communities for the 21st century.
HtmlResAnchor http://www.nrdc.org/cities/smartgrowth

Noise Pollution Clearinghouse (NPC) is a national non-profit organization dedicated to creating more civil cities and more natural rural and wilderness areas by reducing noise pollution at the source.
HtmlResAnchor http://www.nonoise.org

Pima Association of Governments (PAG) is the metropolitan planning organization for the greater Tucson area. PAG coordinates with local governments and the state on issues that cross jurisdictional boundaries such as air quality, water quality and transportation. (It also provides links to all PAG member organizations, such as the Arizona Department of Transportation.)
HtmlResAnchor http://www.pagnet.org

Sierra Club Challenge to Urban Sprawl is calling attention to sprawl with yearly reports, providing resources for activists across the country, and exploring how transportation patterns can be improved to make our neighborhoods safer and more convenient.
HtmlResAnchor http://www.sierraclub.org/sprawl

Surface Transportation Policy Project (STPP) is a non-profit, public interest coalition of over 200 groups devoted to ensuring that transportation policy and investments help conserve energy, protect environmental and aesthetic quality, strengthen the economy, promote social equity, and make communities more livable.

Towerkill.com It is the goal of this website to serve as an information resource on the problem of birds flying into man-made structures and to promote cooperative solutions for mitigating the needless slaughter of millions of songbirds every year.
HtmlResAnchor http://towerkill.com

Tri-State Transportation Campaign (TSTC) is an alliance of public interest, transit advocacy, planning and environmental organizations working to reverse deepening automobile and sprawl development in the New York/New Jersey/Connecticut metropolitan region.
HtmlResAnchor http://www.tstc.org

Urban Land Institute (ULI) provides leadership in the responsible use of land to enhance the total environment.
HtmlResAnchor http://www.uli.org

The Volpe Center is a federal fee-for-service organization within the U.S. Department of Transportation. Work includes air traffic management, highway and rail safety, strategic planning and economic analysis, environmental assessment, transportation logistics, and security.
HtmlResAnchor http://www.volpe.dot.gov

Wildlife Conservation Society (WCS) Metropolitan Conservation Alliance develops innovative locally based strategies that tackle ecosystem loss and urban sprawl in the New York City region.
HtmlResAnchor http://www.wcs.org/home/wild/northamerica

The Wildlife Society (TWS) works to enhance the ability of wildlife professionals to conserve diversity, sustain productivity, and ensure responsible use of wildlife resources for the benefit of society. TWS is considering establishing a Transportation Working Group.
HtmlResAnchor http://www.wildlife.org