Chapter 15
Wildlife Friendly Roads: The Impacts of Roads on Wildlife in Urban Areas and Potential Remedies

Seth P. D. Riley, Justin L. Brown, Jeff A. Sikich, Catherine M. Schoonmaker and Erin E. Boydston

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15.1 Introduction

Roads are one of the most important factors affecting the ability of wildlife to live and move within an urban area. Roads physically replace wildlife habitat and often reduce habitat quality nearby, fragment the remaining habitat, and cause increased mortality through vehicle collisions. Much ecological research on roads has focused on whether animals are successfully crossing roads, or if the road is a barrier to wildlife movement, gene flow, or functional connectivity. Roads can alter survival and reproduction for wildlife, even among species such as birds that cross roads easily. Here we examine the suite of potential impacts of roads on wildlife, but we focus particularly on urban settings. We report on studies, both in the literature and from our own experience, that have addressed wildlife and roads in urban landscapes. Although road ecology is a growing field of study, relatively little of this research, and relatively few mitigation projects, have been done in urban landscapes. We also draw from the available science on road impacts in rural areas when urban case studies have not fully addressed key topics.

We considered urban roads to be roads within urban landscapes, defined as landscapes comprised of significant portions of commercial, industrial, and high-density residential development. However, many urban landscapes include areas with lower density residential development and natural open spaces. In fact, often urban

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S. P. D. Riley (✉) · J. L. Brown · J. A. Sikich · C. M. Schoonmaker
Santa Monica Mountains, National Recreation Area,
401 W. Hillcrest Dr., Thousand Oaks, CA 91360, USA
e-mail: seth_riley@nps.gov

E. E. Boydston
U.S. Geological Survey, Western Ecological Research Center,
401 W. Hillcrest Dr., Thousand Oaks, CA 91360, USA

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roads that pass through or next to open space are particularly important for wildlife conservation and management.

15.1.1 Types of Roads

Variation in the structure (e.g., size, construction materials) and traffic of roads can have profound impacts on how wildlife is affected by them. This variation can include presence of a median, composition of the median, presence and height of fences or walls, and in particular the nature of the surrounding land use (commercial, industrial, residential, agricultural, natural).

The largest roads with the fastest traffic are generally called freeways. Freeways are divided roadways with on- and off-ramps, no traffic signals, and high speed limits. Their size can vary from one or two lanes each way up to five or more. These roads eliminate significant habitat and represent a wide, bare, and formidable area for wildlife to traverse. Traffic volumes can be high on freeways, especially in urban areas. Freeways often require significant engineering and earth movement because of their size and the need for entrance and exit ramps, and they are often built far above or below the surrounding land. Elevated roads on posts facilitate wildlife passage underneath. However, if roads are built on soil or fill, even if vegetated, or sunken down below the surrounding area, they can represent an even greater barrier to wildlife than a paved road surface at grade. Highways are generally smaller than freeways, and typically have traffic regulation such as stoplights. However, highways can overlap significantly in attributes with smaller freeways or larger secondary roads, so the impacts of highways on wildlife largely reflect those of freeways or secondary roads depending on structural similarities. Highways and freeways are often divided, which can increase the overall width of the road corridor, increasing the barrier effects. Additionally, if the median is vegetated, it may draw animals to the road and increase the chance of mortality.

Smaller and generally less-trafficked roads that feed into highways or freeways are secondary roads. Because these secondary roads go through towns and cities, they often have significant development along them. The impacts of urban development immediately adjacent to secondary (or larger) roads interact with the impact of the road itself to further limit animal movement across the landscape. Where there is natural open space in cities, major secondary roads may go through or along natural areas. In these instances, roads have the potential to be significant sources of mortality (e.g., Riley et al. 2003). The incentive for animals to move across roads bisecting natural habitat is great, because animals may perceive habitat on the other side. Moreover, the lack of development along these road segments or the medians within them generally make them less of a barrier than larger urban freeways, but their traffic volume may still be high, contributing to the effects on survivorship.

In urban areas there are also tertiary roads that go through or between residential areas. These roads have relatively few driveways and may have speed limits > the 25 mph typical for residential neighborhoods. Because of their greater traffic volumes and speeds, these roads may often have a significant mortality effect, especially where they are bordering or traversing natural areas (Baker et al. 2007;

van Langevelde et al. 2009). These tertiary roads are typically just one lane in each direction, and while they may be barriers for smaller species, they are less likely to impede movement for larger carnivores and ungulates. Finally, there are also smaller residential roads, where the speed limit is generally 25 mph or less, driveways intersect the road often, and traffic is light. The least traveled of these are likely to be dead-end roads, or cul-de-sacs, where there is no through-access to other streets. In the USA, small urban roads that provide service between neighborhoods and arterial roads (tertiary roads) average about 4300 cars/day, and the urban arterial surface roads (secondary roads) average 15,612 cars/day (U.S. Dept. of Transportation 2011).

15.1.2 Road Effects

There are three broad ways by which roads impact wildlife. First, roads physically replace whatever was previously on the site. Typically roads replace some kind of open space and associated vegetation. This results in a linear area that may be quite wide, is no longer vegetated, and consists of unnatural substrate (asphalt, cement). So the road itself results in a loss of habitat and creates a large bare area, both of which can have a significant impact on the behavior of wildlife.

Second, the habitat and surrounding environment is significantly altered. In fact, Forman (2000) estimated that one fifth of the area of the USA was affected ecologically by roads. Vegetation is generally cleared immediately adjacent to the road, and fences or walls are often added. New, nonnative vegetation may be planted, or existing vegetation may be altered along the road. There may be a median between the directions of larger roads, which may be vegetated or fenced with guardrails or Jersey barriers. Road maintenance, chemicals applied to roadways (e.g., salt, herbicides, oil), artificial lighting, and traffic noise further alter the environment. For wildlife, many of these alterations are negative, and may extend far away from the road itself, although some effects can be positive for particular species.

Third, vehicles traveling on roads cause mortality for wildlife and affect wildlife behavior. Road impacts from habitat loss or alteration would still be present even if no cars were traveling on the road, but the vehicles themselves have a major impact. The extent to which vehicles affect wildlife communities depends on the speed, volume, and timing of the vehicle traffic.

All three of these things represent effects of roads in any landscape. However, here we are interested specifically in how urban roads affect wildlife, and how these impacts may be similar to or different from roads outside of cities in more rural or natural settings. For example, removal of habitat for an urban road may not be important if the road traverses an intensely developed area lacking wildlife. Conversely, if the urban road replaces even a small remaining patch of rare wildlife habitat, the impact may be disproportionately large. In terms of the surrounding habitat, the effects of the road may be particularly strong in urban areas if more light is needed for high-traffic volumes or tall sound walls are required to protect neighboring residential areas. On the other hand, the often vegetated and sometimes relatively natural areas along the road in an intensely urbanized landscape may provide valuable movement corridors that larger mammals can use to move through highly urban landscapes. Finally, traffic characteristics are different in urban areas. Traffic volumes are generally much greater than in rural areas, but speeds will often be lower. These higher volumes but lower speeds are likely to increase the barrier effects of roads, because animals are less likely to attempt to cross; however, wildlife mortality from vehicle collisions may be lower when speeds are reduced.

15.2 Impacts of Roads in Urban Areas

15.2.1 Road Mortality

Perhaps the most obvious and direct threat to wildlife from urban roads is the threat of mortality from being struck and killed by a vehicle. Within the USA alone, there are over 4 million miles of roads, with 27 % of these classified as urban roads (U.S. Dept. of Transportation 2011). In 2005, there were 1.9 million vehicle miles driven per mile of urban road as compared to 0.35 million miles driven per mile of rural road (Federal Highways Administration 2008), a more than 5-fold difference in the amount of traffic on average. The heavier traffic volumes and the high density of urban roads make them an important potential source of mortality for wildlife (Hodson 1965; Rosen and Lowe 1994; Fahrig et al. 1995; Lodé 2000). For many urban wildlife populations, wildlife–vehicle collisions (WVCs) are the primary source of mortality (Grinder and Krausman 2001a; Lopez et al. 2003; Cypher et al. 2009; Cypher 2010; Soulsbury et al. 2010).

Roads serve as a constant threat for many urban wildlife species which are forced to cross roads seasonally for dispersal or breeding, or more regularly (even daily) for animals that must move between habitat patches separated by roads (Atwood et al. 2004; Gosselink et al. 2007; Gehrt and Riley 2010). For many smaller species (such as reptiles, amphibians, and small mammals), it can be incredibly difficult to successfully cross roads, and mortality rates can reach 100 % (Aresco 2005). Larger and more mobile urban animals, such as carnivores or ungulates, are typically capable of crossing roads, but the high density and grid pattern of roads still create significant mortality risk by forcing large animals to make frequent crossings. Riley et al. (2006) documented that 52 % of coyotes (*Canis latrans*) and 40 % of bobcats (*Lynx rufus*) in an urban landscape near Los Angeles crossed major secondary roads. Interestingly, the risk of dying from a WVC was independent of how urban-associated (based on radio-tracking) animals were (Riley et al. 2003), and even animals living mostly within protected natural areas were at risk of mortality on roads passing through open space. Within urban landscapes, it may be more difficult for wildlife to access safe crossing points because roadside development has blocked at least one side of the road. In a study of 15 potential wildlife crossing points north of Los Angeles, Ng et al. (2004) found that the presence of natural habitat on both sides of the road was the most significant factor associated with use by bobcats and coyotes, although not for raccoons (*Procyon lotor*) which used all studied crossing points.

Some urban animals may be exposed to roads frequently enough that they learn how to cross them safely and may have reduced risk of WVCs, thus benefitting from the length of time they are able to survive along roads (Mumme et al. 2000; Erritzoe et al. 2003). Populations of species that flourish in urban areas may have developed ways to avoid WVCs through road avoidance, learned crossing techniques, or exploitation of roadside resources without attempting to cross. Sometimes animals that rarely cross roads are more vulnerable to mortality (Riley 2006), and coyotes in Chicago have been seen to look both ways before crossing streets (JLB, personal observation). More specific study of the reactions and vulnerability of individual animals to roads is needed (e.g., Grilo et al. 2012).

Many factors can affect the likelihood of WVCs in urban areas. Often wildlife is attracted to roads for resources on or near them, which can include garbage (Dill 1926), spilled grain (Forman and Alexander 1998; Boves and Belthoff 2012), insects (Jackson 2003), worms (Gouar et al. 2011), small mammals (Boves and Belthoff 2012), carrion (Finnis 1960; Hodson 1962; Fulton et al. 2008), and fruiting vegetation (Watts 2003; Dowler and Swanson 1982), some of which (e.g., trash) may be especially plentiful along urban roads. There are also other potential attractions along roads such as grit or salt (Mineau and Brownlee 2005; Leblond et al. 2006), basking areas (Lebboroni and Corti 2006), soft dirt for dust bathing, puddles for drinking and bathing, mud for nest building, and hard surfaces for breaking snails (Finnis 1960; Hodson 1962) that may result in WVCs. In a study of moose (*Alces alces*) in the city of Quebec, Canada, modeling indicated that removing salt pools from roadsides and placing them farther away could reduce moose–vehicle collisions (Grosman et al. 2011).

Road design can also impact the number of WVCs that occur. Roads that are raised or lowered or that have embankments may have altered rates of WVCs, although studies have shown some conflicting results. In some cases the WVCs rate was greater on roads that were level with the surrounding landscape (Pons 2000; Clevenger et al. 2003), while Lodé (2000) found that mammals were more commonly found on sunken sections of road while other vertebrates were found on raised roads (see also Grilo et al. 2012). Road width is important, particularly for slower-moving species, because wide roads take longer to cross. Urban roads are often wider to accommodate increased traffic. In general, wider roads also have greater traffic volumes, making it difficult to differentiate road width effects from traffic volume effects. Certain species, particularly smaller ones, avoid venturing across areas devoid of cover, making wider roads an important barrier for these species (Oxley et al. 1974; McGregor et al. 2008; Brehme et al. 2013), but potentially reducing mortality effects by preventing crossing attempts altogether.

Roadside and median vegetation can play an important role in road mortality for wildlife (e.g., Found and Boyce 2011). Tall roadside vegetation makes it difficult for motorists to see wildlife adjacent to the road (Grilo et al. 2009), but it can also be beneficial as it forces birds to fly higher and avoid vehicles (Clevenger et al. 2003;

Ramp et al. 2006), as well as causing drivers to drive more slowly (Lewis-Evans and Charlton 2006). Birds are most likely to be hit by vehicles when they forage, nest, or roost near roads (Hill and Hockin 1992; Erritzoe et al. 2003). Fruiting roadside vegetation has led to large numbers of WVCs in some cases (Watts 2003). During a 1-month period, 298 Cedar Waxings (*Bombycilla cedrorum*) were struck by vehicles while foraging on the fruit of silverberry *(Eleagnus pungens*) planted in the median of a four-lane highway in an urban area in Texas (Dowler and Swanson 1982). Orlowski (2008) found high vehicle mortality for birds where hedgerows and tree belts were adjacent to roads, and he suggested planting vegetation further away to reduce mortality.

Traffic volume is generally positively associated with mortality. Mortality for amphibians and reptiles is positively correlated with traffic volume and can lead to a reduction in adjacent populations (Fahrig et al. 1995). However, mortality can also decrease at very high traffic levels because animals are less willing to cross when traffic volumes increase above a certain level (Ng 2000; Clevenger et al. 2003; Riley et al. 2006). Many studies have found that mortality peaks at a certain traffic volume, and that at and above this level the road serves as a barrier (e.g., Seiler (2005) suggested 5000 vehicles/day was a barrier for Moose). In New Zealand, Brockie et al. (2009) reported that a traffic volume of 3000 cars/day served as a barrier and fewer animals were struck on the road. In a review, Charry and Jones (2009) found variability among studies, but that roads with traffic levels above 10,000 vehicles/day were complete barriers for all terrestrial vertebrate groups with a threshold as low as 6000 vehicles/day for certain groups, such as turtles. Reijnen et al. (1996) found that above 5000 vehicles/day, 7 out of 12 bird species had 12–56 % lower population densities within 100 m of the road, but that above 50,000 vehicles/day all species were reduced. This study measured nearby densities instead of road mortality, but it may be that traffic volume as a barrier is less applicable for birds that are flying above and around the road, and greater volumes will continue to increase mortality.

In response to greater traffic volumes in urban areas, wildlife species may adapt their behavior to cross roads at night or during other times of reduced traffic volume (Kitchen et al. 2000; Grinder and Krausman 2001b; Riley et al. 2003; Bautista et al. 2004; Baker et al. 2007). Mortality rates may be greater where traffic volumes are more variable across seasons or throughout the 24-h day and night cycle, especially if the lower traffic volumes dip below the level necessary for the road to be perceived as a barrier.

For larger and faster species such as carnivores and ungulates, traffic speeds may impact WVCs rates more than traffic volume. In Sweden, 57 % of all moose–vehicle collisions occurred in areas with a speed limit of 90 km/h, while areas with both lower and higher speed limits experienced fewer collisions (Seiler 2005). In the USA along Interstate 80 in Nebraska, average vehicle speed dropped from 106.2–122.5 km/h during 1969–1973 to 88.5–94.3 km/h during 1974–1975, with an associated 34 % drop in road mortalities for all wildlife species combined (specifically medium to large mammals and pheasants (*Phasianus colchicus*; Case 1978)). Most species benefited from the reduced speed, but not all (e.g., white-tailed deer

(*Odocoileus virginianus*) and badgers (*Taxidea taxus*)). Even small changes in traffic speed can have dramatic impacts on wildlife. For example in Cradle Mountain-Lake St. Clair National Park in Tasmania, increases of only 20 km/h on the access road led to the local extinction of eastern quolls (*Dasyurus viverrinus*) and a 50% reduction in Tasmanian devils (*Sarcophilus harrisii*; Jones 2000). After various tools were employed to return traffic to the original speed and deterrents were used to reduce the amount of wildlife crossing the road, eastern quolls were able to recolonize the area and their population recovered to 50% of its former level. This sensitivity to traffic speed means wildlife stand to benefit greatly from the various "safe streets" initiatives aimed at reducing pedestrian and cyclist mortality by slowing and calming traffic (http://www.smartgrowthamerica.org/complete-streets). Even when speed limits are lowered in urban areas, drivers may travel at higher speeds at night, which could increase the threat to nocturnal wildlife (Ramp and Ben-Ami 2006), especially if animals shift their activity to night time hours in more developed areas (e.g., Riley et al. 2003).

Roads near wetlands and riparian areas can have dramatic impacts on semiaquatic vertebrate species and result in extensive road mortality and ultimately population declines (MacDonald et al. 1994; Ashley and Robinson 1996; Fahrig et al. 2001; Hels and Buchwald 2001; Aresco 2005; Shepard et al. 2008; Patrick and Gibbs 2010). Roads that bisect important migratory corridors without the presence of suitable fencing and culverts can be particularly detrimental to semiaquatic wildlife through WVCs sustained when attempting to access critical resources, such as amphibians traveling to breeding sites (Santos et al. 2007; Shepard et al. 2008). Certain populations of turtles appear to be attracted to urban wetlands, because these wetlands rarely dry up and are connected by culvert crossings allowing turtles to move safely between sites (Rees et al. 2009; Roe et al. 2011), indicating that semiaquatic populations can be protected even in urban landscapes.

Age, sex, and seasonality can all be important factors affecting the rate of road mortality. Boves and Belthoff (2012) found that barn owls (*Tyto alba*) were more susceptible to WVCs during the winter, likely because higher energetic demands cause the owls to spend more time hunting or feeding on or near roads. They also found that juveniles, which are more likely to disperse long distances, and females were more frequently killed by vehicles. Road mortality accounted for 40–50% of all mortality in swamp wallabies (*Wallabia bicolor*) in a periurban area in Australia, and juveniles had a 50% greater road mortality rate than adults (Ramp and Ben-Ami 2006). In a study of bats in Pennsylvania, Russell et al. (2009) found that nonreproductive females were more susceptible to WVCs than males, but that there was no apparent age bias. Seasonality of roadkill may vary by taxa; Clevenger et al. (2003) found that in Canada, mammals killed by vehicles were most frequently found in April, birds from May to August, and amphibians from June to August, with the majority occurring during two different rainfall events. In one of the most complete studies of road effects in an urban wildlife population, Lopez et al. (2003) found that male Florida Key deer (*O. virginianus clavium*) are more susceptible than females, especially in the fall, and deer that live closer to the road (US 1) are more vulnerable.

Mortality from vehicles is typically not thought to impact population density for common species (Hodson 1965), but it may have detrimental long-term effects on population health, and for rarer species it can add to natural causes of mortality and lead to a population decline (e.g., Florida Scrub-jays (*Aphelocoma coerlecens*), Mumme et al. 2000). Often, animals killed by vehicles are healthy (Sutton 1927) and in better condition than those that are killed by predators (Bujoczek et al. 2011). For endangered Key deer in Florida, vehicles were the main cause of mortality (>50%; Lopez et al. 2003), most vehicle mortalities were in good to excellent condition (Nettles et al. 2002), and population modeling indicated that South Big Pine Key, the more urban area with higher road mortality, was a population sink (Harveson et al. 2004). As road mortality is likely to be important for many urban populations and is likely to be an additive mortality source, it may often contribute to urban populations being less stable.

15.2.2 Road Effects on Movement and Gene Flow

Along with their effects on survival through WVCs, roads also affect wildlife by creating a barrier to movement. Barrier effects occur when animals are unable to approach or cross roads, turning continuous populations into subpopulations and potentially separating animals from valuable resources. Gene flow is inhibited when breeding individuals do not cross roads or are killed crossing roads. In urban areas, road networks become very dense, separating wildlife into small, disconnected populations that are vulnerable to extinction (Underhill and Angold 2000; Anderson et al. 2011). Many urban roads exhibit high traffic volumes that may exceed 3000–5000 vehicles/day, levels where roads often become barriers (Clevenger et al. 2003; Seiler 2005; Federal Highways Administration 2008; Brockie et al. 2009; Charry and Jones 2009). Accordingly, the barrier effect from roads may be one of the most important impacts on wildlife in urban areas.

For most species studied in urban landscapes, roads act as a barrier to movement and often as a home range boundary. The barrier effects can be especially strong for smaller species, but barrier effects are frequently present for large vertebrates as well. For example, bobcats and coyotes in urban southern California often maintain home ranges with roads (including freeways) or other development as boundaries (Riley et al. 2003, 2006). Hedgehogs (*Erinaceus europaeus*) in England never crossed large urban roads, and crossed small urban roads less than expected (Rondinini and Doncaster 2002). In some cases, even smaller rural highways may create significant barriers to movement and result in home ranges abutting the road. This was the case with some bobcats in northern California (Riley 2006) and with bobcats along a highway through an agricultural area in southern California (Brown and Riley 2014; Fig. 15.1).

Although freeways may form barriers for many animals including bobcats, coyotes, and mountain lions (*Puma concolor*; Riley et al. 2006, 2014), these species are capable of crossing medium-sized urban roads regularly (Riley et al. 2003;

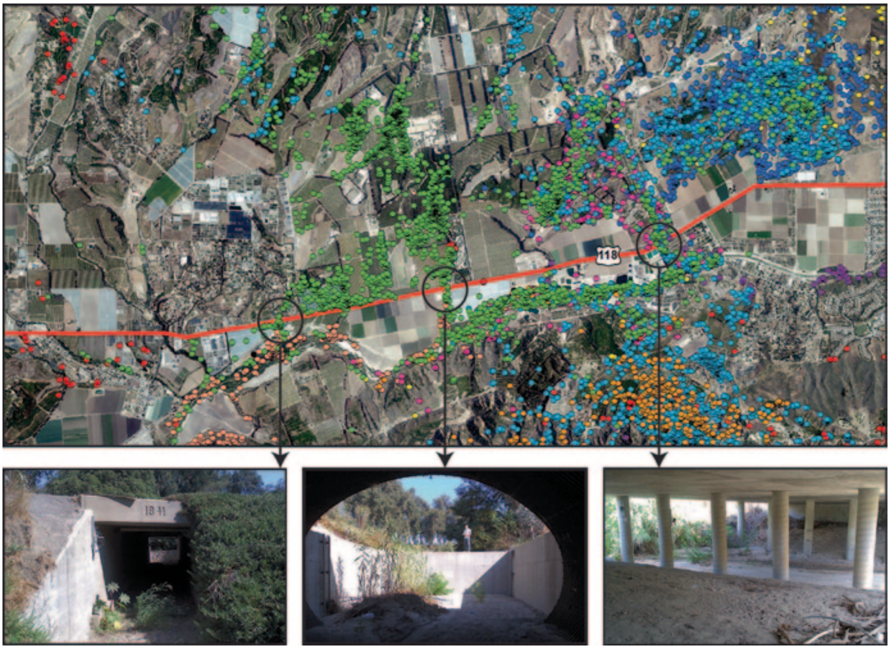

Fig. 15.1 Location data for 9 GPS-collared bobcats (individuals represented by *different colors*) that were tracked during 2012–2013 along State Route 118 in Ventura County, California, a two-lane highway. Even for this road that was relatively small and had relatively low-traffic volume, bobcats rarely crossed except by using three culverts: (from *left* to *right*) a box culvert, a round culvert in a dead-end channel, and a bridge underpass (Brown and Riley 2014)

Beier et al. 2010). Many species, including coyotes (Atwood et al. 2004; Gehrt and Riley 2010), raccoons (Hadidian et al. 2010), red foxes (*Vulpes vulpes*; Soulsbury et al. 2010), and bobcats (Riley et al. 2010), maintain smaller home ranges in urban areas. When those home ranges are largely within natural areas, smaller home ranges can mean that animals encounter fewer roads, despite the high road densities in cities. Additionally, some animals may shift their home range to avoid certain roads (Brody and Pelton 1989) or use their home range in ways that reduce the number of road crossings needed (Baker et al. 2007). These behavioral changes allow some mobile species to live and even thrive in urban landscapes despite high road densities and heavy traffic volumes (Grinder and Krausman 2001a; Prange et al. 2003; Gehrt 2006; Baker et al. 2007; Cypher 2010).

The barrier effect of roads can be especially severe for smaller, less mobile species. An early but striking example of the isolation effect that roads can have was demonstrated in a population of Malaysian house rats (*Rattus rattus diardi*) isolated in a small area (100 acres, 40 ha) completely surrounded by roads. Every rat captured in the population was infested with the mites that serve as the vector for scrub typhus. No mite infestation was detected in the adjacent populations in any direction (Lawley 1957). More recent and direct studies have shown that small mammals avoid crossing even smaller roads. Even dirt roads can be barriers for small vertebrates that avoid open areas, and small paved roads with little traffic can be strong barriers (Brehme et al. 2013). Many motorists in urban areas have experienced a squirrel (*Sciuridae*) suddenly darting in front of their car, but these crossings may actually be rare relative to overall movements by these animals. Studies show that rodents avoid roads, and that as roads increase in size, crossings are less frequent (Oxley et al. 1974; Clark et al. 2001; Rico et al. 2007; McGregor et al. 2008). McGregor et al. (2008) found translocated small mammals were capable of crossing roads, but they were less likely to return to their home range than animals not translocated across roads, and that the road itself served as the barrier to movement rather than traffic, emissions, or noise. More study is needed of small vertebrates and urban roads, but strong evidence that even small roads inhibit movement coupled with the high road densities in urban areas suggest that many of their populations face increased population isolation in urban landscapes.

Species that persist in urban landscapes may still be negatively affected from genetic differentiation and the loss of genetic diversity through drift and inbreeding associated with fragmentation from roads. In a review, Holderegger and Di Giulio (2010) found roads increase genetic differentiation and reduce genetic diversity, despite the fact that road barriers are relatively recent. In an early example, European common frogs (*Rana temporaria)* showed significant genetic differentiation and reduced diversity in populations separated by roads and railroads (Reh and Seitz 1990). Noël et al. (2006) found that eastern red-backed salamanders (*Plethodon cinereus*) exhibited significant genetic differentiation and reduced genetic diversity in habitat fragmented by roads in Montreal, while populations in contiguous habitat did not. Delaney et al. (2010) found genetic divergence associated with fragmentation, in a similar pattern, for three divergent lizard and one bird species, and the presence of major secondary roads between fragments was a significant factor associated with differentiation in all four. Even for larger, more mobile species, larger urban roads can act as barriers to gene flow. Riley et al. (2006) found genetic differentiation across a busy freeway (US 101) in southern California for both bobcats and coyotes after just 50 years or 25 generations, at least twice as much differentiation (as measured by F_{ST} values) across the freeway as between subpopulations on the same side. This same freeway is also a barrier to gene flow for mountain lions; in the small, isolated population in the Santa Monica Mountains south of US 101, genetic diversity is lower than anywhere else in the west, with the exception of an other isolated population in southern California (Riley et al. 2014). Recently, Serieys et al. (2014) examined the genetics of bobcat populations across a wider region surrounding the Santa Monica Mountains and confirmed genetic differentiation between bobcat populations across US 101, but also found a similar level of differentiation across another busy freeway, Interstate 405 (I-405). In this landscape in southern California, as in many urban areas, the freeways are corridors for development, so it can be difficult to distinguish between barrier effects related specifically to the road, to urban development, or to both (see also Sect. 15.3).

Mills and Allendorf (1996) recommended that a minimum of one to ten immigrants per generation need to reach an isolated population to maintain genetic diversity. For species that typically migrate or disperse each year (e.g., amphibians moving to breed), the migration of ten individuals is likely not enough to maintain sufficient reproduction or survival for overall population stability (Mansergh and Scotts 1989; van der Ree et al. 2009). For species such as large carnivores that typically occur at low population densities, it may not be feasible even in ideal situations to reach ten immigrants per generation, although in some cases one effective migrant can make a big difference (Vila et al. 2003; Riley et al. 2014). A further complicating factor is that the number of animals crossing roads is greater than the number of genetic migrants, as many dispersers may not successfully establish territories and reproduce.

Behavioral and social factors may play role in reduced connectivity across roads in urban areas by limiting both the number of migrants and the number that successfully reproduce. The most common type of behavioral barrier is the lack of willingness to cross unvegetated areas (McGregor et al. 2008) or other physical obstacles (e.g., walls or fences). However, because many species set up home range boundaries along roadways, for territorial species there may also be a social barrier to movement that forms in association with roads (Riley et al. 2006). Specifically, when animals encounter the territories of established animals, negative intraspecific interactions may cause the migrant to turn around or keep moving without successfully finding a suitable territory or mate. High densities of individuals located near roads likely strengthen the effect of the social barrier (Riley et al. 2006; Bissonette and Rosa 2009). The ability of animals to successfully cross roads, establish territories, and assist with the maintenance of gene flow is a function of the physical permeability of the road and the surrounding landscape and any behavioral and social barriers. Increasing the permeability of roads may reduce the influence of a social barrier, as increased ease of crossing and more crossing locations should help animals seeking to avoid conspecfics find a vacant territory to occupy.

15.2.3 Roadsides and Edge Effects of Roads (Negative and Positive)

On many highways, the area along the road, or roadside, is wide enough to be considered a distinct habitat type for some animals (Adams and Geis 1983; Taylor and Goldingay 2004; Orlowski 2008). The roadside, also known as roadside right-of-way (ROW), roadside edge, or roadside verge, is designed to uphold the physical integrity of the road and to provide motorists a safe place to pull over. ROWs may extend far away from the road and can vary in their value for wildlife. For example in agricultural areas, roadsides typically consist of exposed dirt edges with open ditches for rain runoff, while roads in forested habitat are surrounded by dense vegetation (Seiler 2001). In urban areas, plantings on roadsides are often designed to be both functional and aesthetically appealing. Planting vegetation along urban roads creates barriers that reduce traffic noise, create wind breaks, and reduce light disturbance for people who live near roads (Taylor and Goldingay 2004; Seiler and

Folkeson 2006). Roadsides in urban areas are generally not created for wildlife use, but the addition of these often well-vegetated corridors can contribute to the value of developed areas for wildlife by providing cover, food, and corridors for movement (Getz et al. 1978; Curtis and Jensen 2004; Fulton et al. 2008; Morgan et al. 2010). Although roadsides have some characteristics that are favorable for wildlife, associated habitat loss, noise pollution, light pollution, traffic, and pesticides can create a hostile environment that deters many species from approaching roads (Hill and Hockin 1992; Forman and Deblinger 2000; Kociolek et al. 2011).

15.2.3.1 Negative Edge Effects of Roads

15.2.3.1.1 Habitat Loss, Alteration by Edge Effects

The loss of natural habitat from construction and roadside maintenance can reduce wildlife activity in roadsides. Roadside vegetation often is trampled or removed during construction, but even after recovery, vegetation clearing adjacent to the road can greatly decrease the abundance and diversity of birds using roadsides, except for scavengers like common ravens (*Corvus corax*; Fulton et al. 2008). Along with reducing habitat, roads introduce artificial edges with sharp changes in vegetation types. Herbicide spraying and mowing along roadsides are used to prevent vegetation from blocking traffic signs, damaging road surfaces, and obstructing driver's views; ultimately they reduce tree cover and favor grasses. The openness of roads and the reduction in vegetation cover also create changes in the microclimate, often increasing temperatures along the road edge relative to more distant areas (Blouin-Demers and Weatherhead 2001). Mader (1984) observed microclimate changes (temperature, humidity) up to 30 m from the edge of a forest road. This change in temperature along the road edge may benefit some reptile species that need warmer areas for thermoregulation (see 15.2.3.2.1), but extreme changes in microclimate along roadside habitats may deter other species such as amphibians that are not able to tolerate desiccating conditions there (Langen et al. 2015).

15.2.3.1.2 Traffic Volume

High-traffic volume can create disturbance along roads and render roadsides unusable for some bird species (Reijnen et al. 1995). A study in Holland determined that disturbance from traffic had effects on three wading bird species: black-tailed godwit (*Limosa limosa*), lapwing (*Vanellus vanellus*), and redshank (*Tringa tetanus*). Traffic disturbance affected individual birds nesting at distances from 500 to 600 m from the road for a quiet rural road and up to 1600–1800 m away for a busy highway, amounting to a 60% reduction in population density that was related to the type of road (Hill and Hockin 1992). Large mammals can also be affected by traffic volume. Singer (1978) found that mountain goats visiting mineral licks showed reactions to vehicles passing on the highway. Grizzly bears (*Ursus arctos*) in Montana showed no or even positive selection for areas surrounding closed roads or roads used by < 10 vehicles/day but avoided areas surrounding roads with > 10 vehicles/day (Mace et al. 1996). In Arizona, elk (*Cervus canadensis*) were more likely to use habitat near the highway when traffic volumes were low (< 100 vehicles/h). Elk shifted away from the highway during times of high vehicle traffic and returned to areas near the road when traffic volumes were lower (Gagnon et al. 2006).

In an urban landscape in southern California, Riley et al. (2003) found that bobcats and coyotes were often located in natural habitat during the day, and that both species were more likely to cross urban roads and venture into developed areas at night when traffic volume and human activity were lower. However, both bobcats and coyotes in this area still used natural habitat near roads even during the day, something that is difficult for them to avoid given the highly fragmented nature of the landscape. In an interesting case, Pescador and Peris (2007) found that predation rates were higher on birds nesting adjacent to roads with medium- to low-traffic volume than on birds nesting near roads with more traffic. They suggest that while predators generally avoid roads with high traffic, WVCs on roads with moderate or low traffic may attract predators and thus increase nest predation along these roads. Overall, however, the high traffic volumes in urban areas will decrease the value of roadsides as wildlife habitat.

15.2.3.1.3 Noise Pollution

One of the negative effects of increased traffic is noise. Traffic noise can cause frequent or chronic disturbance for some species. Forman and Deblinger (2000) report that traffic noise is the primary cause of avian disturbance in roadside habitat, and traffic noise can affect bird communities hundreds of meters from the road, with a reduction in bird abundance and diversity (Reijnen et al. 1995; Forman and Deblinger 2000). The reduction in bird density and diversity along noisy roadways may be in part explained by birds having difficulty communicating through calls and songs. Song sparrows (*Melospiza melodia*) will adjust their vocalizations to reduce masking from urban noise (Wood and Yezerinac 2006), but the small body size of some species may not allow them to produce vocalizations loud enough for conspecifics to hear over the din of urban environments (Brumm 2004). Some bird species are considered to be urban-exploiters; they are able to adapt to the urban environment and seem to be less affected by noise pollution and other urban disturbances. A study in Spain documented a positive relationship between urban-exploiter birds and roads. Urban-exploiter species contributed significantly to the high density of birds in cities and adjacent areas, but bird diversity was lower in these disturbed areas compared to natural areas far from development (Palomino and Carrascal 2006, 2007). Traffic noise can also affect communication of mammals by masking signal reception and creating false alarms. For example, the low frequency of vehicle noise closely overlaps with the frequency created by Stephen's kangaroo rat (*Dipodomys stephensi*) during footdrumming, so that deceptive signals or "false alarms" are generated by vehicle noise, and true alarms are masked (Shier et. al. 2012).

15.2.3.1.4 Light Pollution

Artificial light along roads from light poles, buildings, and car headlights can alter the night time environment for animals in roadsides. In general, the effects of light pollution on wildlife are overwhelmingly negative (Longcore and Rich 2004). Artificial light may increase nighttime foraging opportunities by attracting or making prey easier to see, but predators attracted to these altered conditions are at risk for WVCs. For example, nightjars (*Camprimulgidae spp.*) that have learned to associate roadside lights with flying insects are in danger of being hit by vehicles when they apply their sit-and-wait hunting technique to roadsides, and road mortality can be quite high for adult nightjars (Jackson 2003). Slow-moving toads may also become victims of road mortality as they forage on or near roadways for insects attracted to the light (Langen et al. 2015). Headlights can reduce the ability of animals on the roadway to escape vehicle strikes, as the lights can cause them to freeze in front of an approaching vehicle (Mazerolle et al. 2005). Light pollution is likely to be particularly relevant around roads in urban landscapes, because road lighting will be more extensive for safety reasons, and because commercial and residential development are often present around urban roads.

15.2.3.1.5 Chemicals

Road maintenance activities and vehicles can spread chemical pollutants into roadsides including salt, heavy metals, fertilizers, nutrients, and other toxicants (Seiler and Folkeson 2006). Roadside contaminants can be directly toxic for wildlife or can indirectly affect wildlife by degrading food and cover resources (Mineau and Brownlee 2005; Karraker et al. 2008). Heavy metals can accumulate in the tissue of plants and animals in roadsides, affecting reproduction and survival for small mammals (Scanlon 1987). Road salt used for deicing can have effects on aquatic systems as far as 1500 m away from the road (Forman and Deblinger 2000). Egg and larval survival decreased for spotted salamanders (*Ambystoma maculatum*) and wood frogs (*Rana sylvatica*) as salt concentrations increased in roadside pools (Karraker et al. 2008). The consumption of road salts can negatively affect some species, and salt toxicity may contribute to widespread mortality of birds around roadways (e.g., *cardueline finches*; Mineau and Brownlee 2005). Again in cities, specifically those at higher latitudes where deicing is common, the sheer density of roads is likely to make the problems of salt presence in roadsides severe.

15.2.3.2 Attractions of Roadsides for Wildlife

Roadsides are highly disturbed environments, yet some wildlife species are attracted to the resources available there. Planted areas adjacent to roads can provide nesting sites, shelter, and food (Haner et al. 1996; Palomino and Carrascal 2007; Fulton et al. 2008). In heavily altered landscapes such as urban and agricultural areas, roadsides may represent the only relatively natural habitat in the area and may also provide wildlife with suitable corridors to facilitate movement between fragmented natural areas (Seiler 2001). In Great Britain, roadsides support a great deal of the island's faunal diversity including 40 % of its mammal species, 100 % of the reptiles, 83 % of the amphibians, 20 % of the birds, and 42 % of the butterflies (Way 1977; Forman et al. 2003). Some nations consider roadsides to be of great conservation value and make efforts to protect and enhance natural habitat along roads; in Great Britain, six roadsides are officially designated as sites of special scientific interest (Forman et al. 2003).

15.2.3.2.1 Viable Habitat

Although habitat quality and structure vary throughout the world in roadsides, they can attract and support a variety of species (Baker 1971; Adams and Geis 1983; Bennett 1991; Curtis and Jensen 2004; Taylor and Goldingay 2004; Kociolek et al. 2011). Landscaped vegetation or disturbed grassy verges can increase species richness along roadsides by providing habitat different from the surrounding landscape (Adams and Geis 1983; Haner et al. 1996; Richardson et al. 2006; Palomino and Carrascal 2007). More specifically, shrubs and trees planted along roads can provide valuable nesting sites for birds and small mammals (Adams and Geis 1983; Orlowski 2008). Adams and Geis (1983) actually detected more small mammal species in roadsides than in the adjacent habitat, and determined that roadside habitat was attractive to grassland species but also to less habitat-specific rodents. The openness of roads creates changes in microclimate in roadsides that can provide ectothermic animals with increased opportunities for thermoregulation. For example, Richardson et al. (2006) found that female prairie kingsnakes (*Lampropeltis spp.*) used artificial edges along roads more often than natural edges. Raised embankments along roads may provide habitat in some urban areas, such as in Bakersfield, California where endangered San Joaquin kit foxes (*Vulpes macrotis mutica*) have been found to den in road embankments (Bjurlin and Cypher 2003). Numerous species, including bobcats, coyotes, raccoons, deer, gray foxes (*Urocyon cinereoargenteus*), skunks (*Mephitidae*), squirrels and other rodents, rabbits (*Leporidae*), various bird species, and even mountain lions (Schoonmaker and Riley 2011; Riley et al. unpublished data), utilize natural habitat adjacent to I-405 near Los Angeles (Fig. 15.2). In intensely urban landscapes such as around Los Angeles, wildlife may become habituated to freeway noise and activity, and in turn areas around freeways may represent important areas of habitat in a highly developed landscape.

15.2.3.2.2 Food and Nutrients

Roads may provide an increase in food resources for some wildlife species. Birds and small mammals are drawn to roadsides to forage on seeds that are more easily detected in short grass along mowed areas, berries and fruits from vegetation

Fig. 15.2 Locations of motion-activated cameras (*red stars*) that detected several mammal species, including a mountain lion (*left* photograph) and coyote (*right* photograph) in disturbed habitat along Interstate 405 (I-405) in Los Angeles County, California during 2012 (Riley unpubl. data). Just south of these cameras was one of two bridges over the interstate where camera monitoring showed animals occasionally crossing. (Schoonmaker and Riley 2011; Riley et al. unpublished data)

planted along roads, and invertebrates that are attracted to roads; birds will also collect sand and gravel found on roadsides as grit to help digest food (Laursen 1981; Dowler and Swanson 1982; Stapp and Lindquist 2007; Fulton et al. 2008). Morgan et al. (2010) found that roadsides can have a positive effect on food availability and energy intake for threatened Florida scrub-jays; scrub-jays handled more food items and spent less time foraging along roadsides compared to interior areas. The abundance of small mammals found in roadsides attracts raptors, and the presence of utility poles and fence posts along roads provides them with hunting perches (Hill and Hockin 1992). In open vegetated roadside areas, nutritious grasses, planted crops, and artificial salt pools are all attractants for ungulate species such as deer, moose, and mountain goats (*Oreamnos americanus*; Pletscher 1987; Laurian et al. 2008; Found and Boyce 2011; Clevenger and Huijser 2011). Salt is an important mineral for herbivores, and in areas where natural salt licks are not available, salt pools created by the deicing of roads are major attractants for ungulates (Fraser and Thomas 1982; Pletscher 1987; Laurian et al. 2008). Laurian et al. (2008) found that although moose usually avoided areas within 500 m of roads, some individuals would visit roadsides and feed on vegetation that contained higher levels of sodium than that in adjacent forest areas. In urban areas, roadsides planted with berry producing fruits can be an attractant for omnivorous mammals as well. In a study of coyote diet in an urban landscape in southern California, we found that coyotes consumed a high percentage of fruits from ornamental plants that could be found throughout the urban landscape including in yards, urban parks, and along roadsides (Gehrt and Riley 2010).

15.2.3.2.3 Corridors

In some instances roadsides may function as corridors (e.g., James and Stuart-Smith 2000), and in relatively hostile landscapes that are difficult to navigate, including densely urbanized ones, these roadside corridors could facilitate dispersal between fragmented natural areas. Meadow voles (*Microtus pennsylvanicus*) dispersed over 100 km in 6 years along grassy roadsides in Illinois (Getz et al. 1978). In the Netherlands, bank voles (*Clethrinomys glareolus*) traveled along wooded verges of rail and motorways to colonize the Zuid-Beveland peninsula (Seiler 2001). Young hedgehogs in England regularly dispersed along roadsides (Rondinini and Doncaster 2002). Road surfaces may even facilitate dispersal and have led to range expansion for some species. Cane toads (*Rhinella marina*), an introduced species to Australia, moved into previously inaccessible areas via roads (Seabrook and Dettmann 1996). Although roadsides may facilitate dispersal and movement for some species, they may also be challenging to navigate for long distances because road maintenance, construction, and embankments can form barriers along the way. Perhaps most importantly, road corridors are likely to intersect other roads, especially in urban areas, forcing animals to risk crossing the perpendicular road or creating a barrier for species not willing to cross. The use of roadsides as corridors may be more common for species that are less affected by the disturbance and habitat alteration present there.

15.3 Planning and Placement of Roads in Urban Areas

To accommodate urban growth, cities modify and expand their road networks, increasing the challenges for wildlife persistence in urban areas. However, including considerations for wildlife as early as possible in urban transportation planning can help mitigate impacts to animal populations. The most important opportunity to influence the outcome for wildlife lies in determining the path of the road across the landscape. Minimizing further habitat fragmentation from new roads may be particularly important for wildlife in urban areas where open space is already at a premium. One strategy to minimize fragmentation is “bundling” of roads—placing new roads near existing roads or other development rather than constructing new road paths through open space (Jaeger et al. 2005; Levin et al. 2007). This strategy may result in roads that trace the edges of the urban-wildland interface or in a wider road footprint if a new road runs beside an existing one. Another approach is limiting the length of road that bisects natural habitat by moving it to the narrowest part of the natural area. However, a tradeoff is that all of these approaches could lead to longer, more sinuous roads and an increase in road density (Gibbs and Shriver 2002; Rytwinski and Fahrig 2007).

Modifications of existing roads may offer ways to meet transportation needs without additional habitat fragmentation, but increasing traffic carrying capacity of roads may increase their barrier effects. Perhaps the most common form of mitigation for the barrier effects of roads is to provide safe passage for animals under or over roads while preventing them from accessing the road's surface (Clevenger and Waltho 2005; Grilo et al. 2008; Glista et al. 2009). Sites targeted for mitigation often include areas where habitat abuts both sides of the road, areas where high numbers of animals are hit and killed by vehicles (Barnum 2003; Grilo et al. 2008), or where roads isolate subpopulations of a species (Riley et al. 2006; Delaney et al. 2010). Predictive models for the impacts to wildlife can also aid in the selection of locations for crossing structures in the design of new roads. Because mitigation costs can be very high, particularly for new construction of underpasses and overpasses, prioritization and improvements for wildlife may often be a compromise between the ideal solutions for wildlife and available resources. However, there should be reasonable confidence that any measures undertaken will have value for wildlife and meet goals.

Changes to existing roads may present opportunities to insert mitigation measures for wildlife that were absent from the original design of a road or to offset negative impacts to wildlife when the traffic carrying capacity of a road is increased. For example, installation of wildlife fencing and new wildlife crossing structures were included as part of a substantial widening of State Route 71 in the Los Angeles-Orange County metro area. The original, narrower road had several culverts for drainage purposes, and the widened road included structures designed for wildlife use. A study before and after these changes found that connectivity for bobcats and coyotes did not decrease after freeway expansion and may have improved despite the widening of the highway (Alonso et al. 2014). Similarly, widening of the I-405 Freeway in Los Angeles included wildlife friendly modifications of a road bridge to decrease barrier effects and facilitate wildlife movement (Schoonmaker and Riley 2011).

Integrating road planning across the larger urban landscape can help a community meet transportation infrastructure needs while limiting adverse impacts to ecological connections for wildlife. Landscape connectivity plans or linkage maps that show priority areas for connectivity, such as Habitat Conservation Plans, exist for some large regions facing rapid development (e.g., Beier et al. 2006), and methods for designing linkages can be generalized to other areas (Beier et al. 2008). Furthermore, such planning that is often done for vast landscapes may be "downscaled" from broad regional plans to smaller urban areas that are more constrained by development (e.g., Thorne et al. 2006; Balkenhol and Waits 2009). Competing and conflicting interests between transportation and wildlife conservation goals, and potential cost limitations, are challenges to wildlife friendly improvements, but reducing WVCs and maintaining natural, intact areas of open space in cities are examples of outcomes that can benefit both humans and wildlife.

15.4 Mitigation of Negative Road Impacts in Urban Areas

As the science of road ecology has evolved, so have the collective efforts by public agencies and environmental stakeholders to mitigate the negative effects of roads on wildlife (Beckmann et al. 2010). These mitigation measures attempt to minimize the harmful ecological impacts of roads on wildlife populations, although mitigation alone cannot eliminate the detrimental impacts of roads. The most successful conservation efforts reduce WVCs and increase connectivity for a range of species. Despite the prevalence and importance of roads in urban landscapes, there are actually few studies explicitly studying mitigation efforts for roads in urban areas. Where possible, we have drawn on our own experience with wildlife and roads in southern California.

One of the most critical aspects of any effort to reduce the impacts of roads is selecting their location. There are various methods for producing connectivity or linkage maps (Beier et al. 2008). A critical element for any mitigation measure is that natural habitat remains on both sides of the road, and in many urban areas it is rare to have natural area abutting freeways or other major roads on one side, let alone both. For example, for the US 101 Freeway in southern California which separates the Santa Monica Mountains from open space to the north, there are very few places left where it is feasible to place crossing structures (Fig. 15.3). Considering wildlife connectivity needs and mortality risks before urban landscapes reach this point allows more options, at considerably less political and monetary expense.

15.4.1 Facilitating Movement: Crossing Structures

Wildlife crossing structures allow animals to safely move across a roadway, therefore maintaining habitat and population connectivity, reducing WVCs, and increasing motorist safety. Wildlife crossings come in a variety of shapes and sizes and include tunnels, culverts, and bridge underpasses going under roads, and road, wildlife, and canopy bridges going over roads (Forman et al. 2003; Glista et al. 2009). Crossing structures have been engineered and incorporated into road construction and improvement projects for road mitigation in many parts of the world (Forman et al. 2003). Many, if not most, crossing structures were not originally designed to facilitate wildlife movement (e.g., drainage culverts), but they have been found to benefit a variety of species (Haas 2000; Clevenger et al. 2001a; Ng et al. 2004).

Different types of animals require different wildlife crossing structures. For example, small mammals may prefer to use pipes or small culverts, while some ungulates and large carnivores select vegetated overpasses. In one study, grizzly bears, deer, and elk used overpasses more than underpasses, while black bears (*Ursus americanus*) and mountain lions used underpasses more frequently than overpasses (Clevenger and Waltho 2005). The location, type, and dimensions of a structure, as well as the habitat surrounding it, are all critical parameters that will determine use

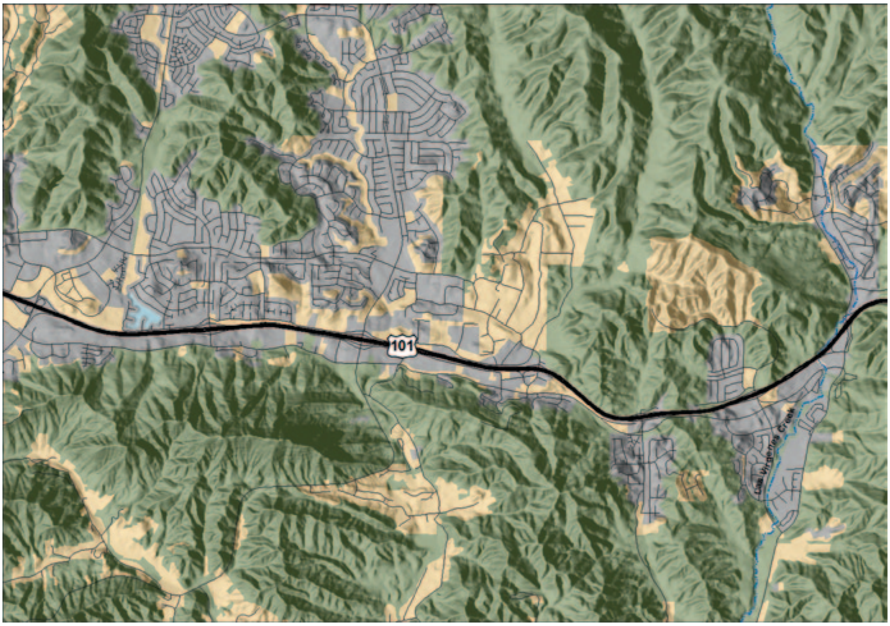

Fig. 15.3 Urbanization abuts much of US 101 such as along this 10 km stretch in Ventura and Los Angeles Counties, California, parallel to the Santa Monica Mountains to the south. Because the Freeway is also a development corridor, locations where natural habitat abuts the freeway are very limited. Moreover, the surrounding urbanization creates long narrow corridors perpendicular to the freeway before animals reach larger, more contiguous open space. For example, there is a culvert where Las Virgenes Creek (*thin blue line*, *right* side of image) crosses under the freeway, but the stream is surrounded by development for over a kilometer both north and south of US 101

by wildlife. For underpasses, variables including the length, width, and height of the structure and the presence of habitat on either side of the passage are important predictors of crossing for some species (Haas 2000; Forman et al. 2003; Ng et al. 2004). Ideally crossing structures of various types and sizes are needed at frequent intervals (Bissonette and Cramer 2008) to reduce impacts on the whole wildlife community. At a minimum, it is important to ensure that the crossing structure will be suitable for the species of greatest concern.

15.4.1.1 Overpasses: Types of Bridges for Wildlife Movement Over Roads

15.4.1.1.1 Wildlife Bridges

Wildlife bridges, also known as wildlife overpasses, are structures that are built over roads to allow animals to safely cross. They can range in width from 30 to 50 m on each end narrowing to 8–35 m in the center, to structures over 200 m wide (Jackson and Griffin 2000; Forman et al. 2003). Most wildlife bridges are vegetated and have a continuous strip of soil and native trees, shrubs, and grasses to provide suitable habitat for a variety of species. Wildlife overpasses are usually designed for large mammals (e.g., in Banff National Park, Canada, Clevenger and Waltho 2005), but if habitat is provided, small and medium-sized animals will use them as well (e.g., in the Netherlands, van Wieren and Worm 2001).

Overpass structures often incorporate specific habitat characteristics to attract wildlife. For example, some overpass structures have ponds on each end of the crossing to attract animals and provide habitat for amphibians. Overpasses may incorporate solid walls, earthen berms, dense vegetation, or a combination of these features on the outer edges (the "shoulders") of the bridge to reduce light and noise disturbance for animals and block the view of the moving vehicles below. Small mammals, reptiles, and amphibians will use overpasses if cover is provided in the form of rock piles, logs, and bushes. Specific types of vegetation and strategic placement along a wildlife crossing can encourage crossings by birds and bats (Clevenger and Huijser 2010). Overpasses can even have a guiding-line function for birds to cross roads by following the natural habitat (Forman et al. 2003), as seen in Switzerland where woodland birds crossed a multilane highway using overpass structures (Keller and Pfister 1997).

Advantages of wildlife overpasses relative to crossing structures underneath roads include less confinement, less noise disturbance, and the maintenance of ambient conditions of rainfall, temperature, and light and therefore the ability to accommodate a wider variety of species and even to serve as habitat for smaller animals (Jackson and Griffin 2000). The major disadvantage is that they are usually the most expensive option (Glista et al. 2009). Thus, wildlife overpasses are uncommon, and as far as we know, none have yet been built in urban areas. This may be the result of high costs or because locations for them in urban areas are rare, as they require sufficient natural habitat on both sides of the freeway to accommodate the length and width of the structure. As more agencies and cities consider the importance of wildlife movement across roads, hopefully wildlife bridges will become an important feature in urban landscapes.

15.4.1.1.2 Road Bridges

Road bridges refer to bridges above a major linear element of infrastructure (e.g., a road or a railroad) that allow human access above it, generally via another road (van der Ree 2007). These structures are typically narrow, nonvegetated, and may contain a sidewalk for people. Very little attention has been paid to their potential utility for wildlife, perhaps not surprisingly since they are generally built to move cars, and they connect to roads on either end. However, these types of crossings are common in urban areas and may benefit wildlife in settings where options for connectivity are limited. Road bridges could be adapted for wildlife use by installing soil and vegetation along the edges of the bridge and creating a side path specifically for wildlife use. As with wildlife bridges (Clevenger and Huijser 2010), light and noise disturbance from vehicles may be reduced by using walls or vegetation.

As part of a widening project for the I-405 Freeway in Los Angeles, California, we have been monitoring the use of two existing bridges on I-405 where it passes through the Santa Monica Mountains (Fig. 15.2). We have documented coyotes, raccoons, rabbits, and striped skunks using the nonvegetated pedestrian sidewalks over I-405, and we have identified mule deer and bobcats on the sidewalks for these bridges as well, although they do not appear to have fully crossed the span (Schoonmaker and Riley 2011). As part of the mitigation for the freeway widening, the California Department of Transportation (Caltrans) is widening one of the bridges and adding a "wildlife sidewalk" that will be covered by decomposed granite and visually blocked from the freeway by a wall.

In another wildlife study in Los Angeles, remote cameras detected coyotes and mule deer using two road bridges over the US 101 Freeway as it passes through the Hollywood Hills (Boydston, Cooper, Ordeñana unpubl. data; Fig. 15.4). This same study also detected a mountain lion on the east side of US 101 in Griffith Park, a natural area surrounded by roads and home to the Hollywood sign (Chadwick 2013). Genetic analyses indicate that this animal came from the Santa Monica Mountains to the west (Riley et al. 2014), suggesting that he crossed both I-405 and US 101 Freeways to reach Griffith Park, potentially using road bridges (especially for US 101). If further research indicates that road bridges can assist with connectivity, we may see more designs for them to accommodate wildlife movements.

15.4.1.1.3 Canopy Bridges

Canopy crossings are another type of above-grade crossing structure designed exclusively for semiarboreal and arboreal species that use tree canopies for travel. They are designed to restore connectivity between forested habitats separated by major roadways, and their structure can vary based on the site, road type, road width, and focal species. Some crossings consist of thick ropes or cables that are anchored between trees or permanent fixtures such as signs or light posts (Beckmann et al. 2010). Rope bridge overpasses in northeast Queensland, Australia have been found to provide safe passage routes for arboreal rainforest mammals that are highly susceptible to road mortality (Goosem et al. 2006). In another study, rope bridges restored connectivity for arboreal species across a major highway in southeast Australia; complete crossings were recorded for five species, two of which were endangered, within 2 years of canopy crossing installation (Soanes and van der Ree 2009).

Again, there are no studies of canopy bridges in urban landscapes, as far as we know. However, in contrast to wildlife bridges, canopy bridges may be easy to implement in urban areas. There are many existing vertical structures along urban roads, including signs and lightposts, which could be used at minimal cost. There are also many street trees in cities, including in even the most intensely urbanized downtown areas, and many cities have movements to increase numbers

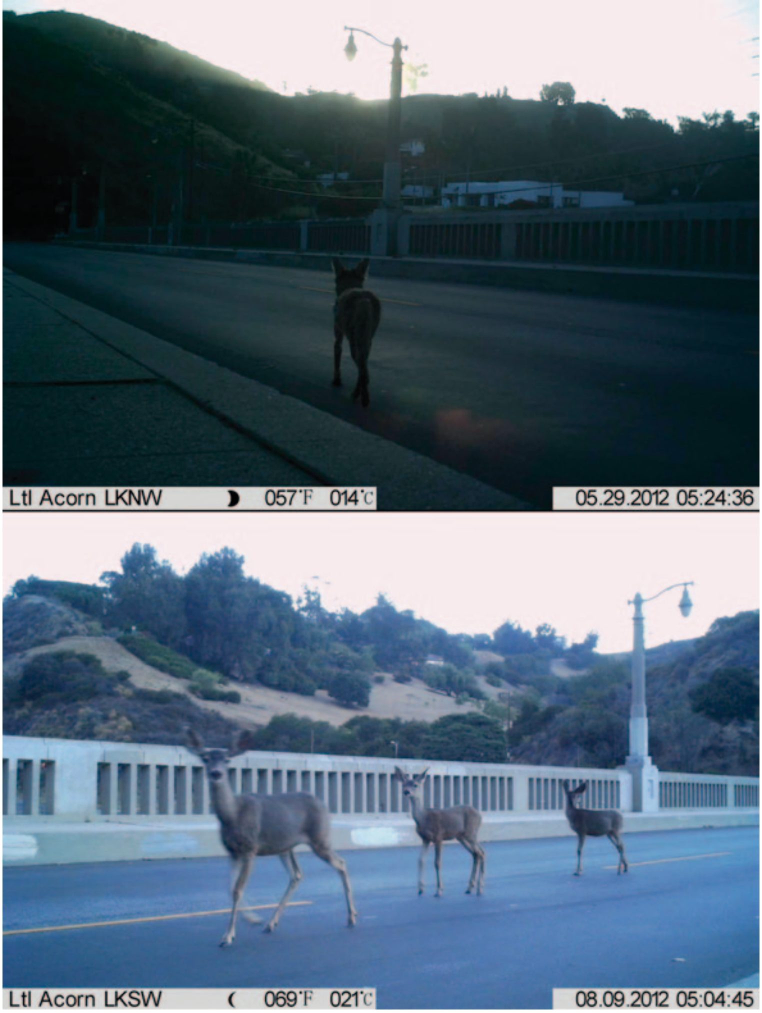

Fig. 15.4. Motion-activated cameras monitoring two bridges over US 101 in the Cahuenga Pass of Los Angeles, California detected occasional use by wildlife such as a coyote (*top* image) and a mule deer with fawns (*lower* image) (Boydston, Cooper, Ordeñana unpubl. data)

of street trees (e.g., the million trees project in New York City). When feasible (taking into consideration safety and maintenance concerns), street trees could be allowed to grow horizontally over roadways, or relatively short ropes or cables could be used to close the gaps, allowing arboreal species such as squirrels to safely cross. In regions where large deciduous trees are common along streets, this could be an effective strategy for reducing squirrel mortality on roads, which is often high especially in the fall when young animals are dispersing. Of course, canopy bridges are limited in that they are only useful for arboreal animals.

15.4.1.2 Underpasses: Structures Allowing Wildlife to Cross Under Roads

Wildlife underpasses include bridge underpasses, culverts, tunnels, and pipes, and their design and dimensions can vary considerably. As might be expected, larger animals require larger structures, although there can be some differences related to taxonomy and behavior as well (e.g., ungulates may be more reluctant to use tunnels than carnivores). Some underpasses have been built exclusively for wildlife use; for example, along Interstate 75 (Alligator Alley) in southern Florida, endangered Florida panthers (*P. concolor coryi*) and other species including bobcats, deer, raccoons, alligators (*Alligator mississippiensis*), and black bears regularly used underpasses specifically constructed for wildlife to safely cross under the highway (Foster and Humphrey 1995). Most tunnels used by wildlife were built for water drainage or human travel, but despite their original intent, these structures can be important linkages for wildlife (Forman et al. 2003; Ng et al. 2004). Moreover, underpasses that were not designed for animal passage can be modified to encourage wildlife use. For example, culverts with flowing water can be outfitted with a dry ledge for animal movement. In dry culverts, natural debris can be placed throughout larger underpasses to provide cover for smaller animals.

15.4.1.2.1 Bridge Underpasses

Bridges built where roads cross rivers, streams, and other roads form underpasses below them that range widely in size and are relatively common in urban areas. Usually built as features of a road rather than for wildlife, these underpasses can be quite valuable for movement by a variety of taxa because the bridges often span natural terrain features (Glista et al. 2009). Bridge underpasses can be adapted or modified (e.g., by adding vegetation) to further facilitate crossing by wildlife, including amphibians and semiaquatic and semiarboreal species (Beckmann et al. 2010).

Underpasses below large bridges typically provide plenty of air movement and light, as well as a sense of openness, which can increase the chances of crossing for many species. The height and width of bridge underpasses (the width of the road or stream, plus any side areas) make them viable even for large or more sensitive species such as ungulates. Bridges with open medians (i.e., where there is space between the lanes going in each direction) provide natural light in the middle which increases passage and can create small areas of natural habitat for small mammals, reptiles, and amphibians, but they are much louder than continuous bridges (Jackson and Griffin 2000). In our studies in the Los Angeles area, we have monitored a number of bridge underpasses along roads that have allowed movement under busy freeways, including I-405 and US 101, which would otherwise be impassable (Ng et al. 2004; Schoonmaker and Riley 2011). However, bridge underpasses in urban areas often cross channelized sections of rivers and streams, with concrete floors and tall, concrete walls, that are designed to accommodate heavy rainfall and may not be conducive for entrance or exit by wildlife.

15.4.1.2.2 Culverts

A culvert is a round or rectangular tunnel that allows water to flow underneath a road. They are usually made of concrete, smooth steel, or corrugated metal and are smaller than bridge underpasses. Depending on their specific characteristics, culverts can provide important avenues for animals to cross under roads and can increase connectivity in fragmented landscapes. Some species that have been shown to use culverts include black bear, mountain lion, wolf (*Canis lupus*), elk, deer, coyote, bobcat, raccoon, river otter (*Lontra canadensis*), nine-banded armadillo (*Dasypus novemcinctus*), Virginia opossum (*Didelphis virginiana*), marten (*Martes americana*), skunk, weasel (*Mustela sp*.), rabbit, squirrels, lizards, snakes, and amphibians (Yanes et al. 1995; Clevenger and Waltho 2000; Clevenger et al. 2001a; Cain et al. 2003; Ng et al. 2004; Dodd et al. 2004). Generally, culverts are larger than tunnels, although carnivores such as bobcats and coyotes will even utilize round pipe culverts that are only a meter in diameter (Alonso et al. 2014).

Concrete box culverts may be more effective than round metal culverts of the same size, because they provide more interior space for the same height and width, and because cement retains moisture and may be more like natural surfaces adjacent to the culvert (Ruediger and DiGiorgio 2007). Although the primary purpose of box culverts is to move water during flash floods and times of heavy rain, they can provide a corridor for many animals throughout the year. The installation of prefabricated box culverts under roads has proven successful in accommodating the movements of wildlife from large, wide-ranging mammals such as Florida panthers and black bears (Land and Lotz 1996; Evink 2002) to small, slow species such as spotted turtles (*Clemmys guttata*) (Kaye et al. 2005). In urban southern California we have recorded multiple species using even long (140 m) culverts, in one case as often as nearly every day for coyotes (Sikich and Riley 2012). Overall, culverts, even if not originally designed for wildlife, can be important for maintaining habitat connectivity across busy highways in an urban, fragmented landscape (Ng et al. 2004).

15.4.1.2.3 Tunnels

Smaller undercrossings such as “amphibian tunnels” and “wildlife pipes” ranging in size from 0.3 to 1.5 m (diameter or height) have been widely used in Europe to facilitate wildlife movement (Forman et al. 2003). These smaller undercrossings are particularly effective for amphibians, reptiles, and small mammals (e.g., Puky et al. 2007 in Hungary), and may be preferred to large structures by small mammals (McDonald and St Clair 2004). Small tunnels have also been effective for addressing fragmentation issues for sensitive species. In an Australian ski resort, the population structure and survival rates of mountain pygmy-possums (*Burramys parvus*) were restored using tunnels filled with rocks to safely cross a road bisecting a breeding area (Mansergh and Scotts 1989). Given the small size of wildlife tunnels, they are certainly amenable to use in urban landscapes. In places where important populations of amphibians or reptiles still exist in urban areas, these tunnels, accompanied by fencing, could be cost-effective solutions to connectivity and mortality concerns.

15.4.2 Reducing Mortality

Various mitigation techniques have been used to reduce WVCs. Most of these techniques can be separated into two categories: those aimed at modifying *human* behavior and those aimed at modifying *animal* behavior (Romin and Bissonette 1996; Forman et al. 2003; Beckmann et al. 2010).

15.4.2.1 Modifying Human Behavior

Public outreach and education to heighten community awareness about the impacts of roads on wildlife can be used to reduce road mortality, especially for sensitive species. We do not know of studies showing that public outreach has resulted in fewer WVCs, but it is still valuable for raising awareness about the problem and for generating public support for other mitigation measures (Beckmann et al. 2010). Warning signs are also regularly used to alert drivers to be watchful for wildlife on roads. However, Meyer (2006) found that standard deer warning signs had little effect in reducing WVCs, likely because drivers become habituated to them and any changed behavior (reduced speed or increased vigilance) disappears over time. Recent efforts have been made to improve warning sign technology, including interactive signs with sensors that detect and activate when large mammals are present near the highway. Night time speed reduction signs and variable message signs are also being used in some states as an alternative to traditional static signs (Ruediger and DiGiorgio 2007).

Temporary road closures are another mitigation measure that modifies human behavior. Such closures have been shown to enhance amphibian migration and reduce mortality during the breeding season (Forman and Alexander 1998). In a national park in Pennsylvania where amphibian mortality was common on roadways, road closures were put into place during the mass migration of five amphibian species and reduced mortality during this critical period (National Park Service 2006). Road closures, as well as people moving amphibians across roads in “bucket brigades” are rarely possible in urban landscapes where traffic is constant and the high demand for roads makes closures impossible. However, in Tilden Park, in Berkeley, California, a road through the park is closed for 5 months every year to protect newts migrating to and from wetlands to breed. This road is within the confines of the park, which makes the closure easier to manage, although even this park road is used by commuters, making the closure contentious.

Increasing the ability of drivers to see animals by adding lighting and removing vegetation (Putman 1997) may help reduce wildlife strikes along roads (Beckmann et al. 2010). Although some studies have shown reductions of large-mammal vehicle collisions by employing these techniques (Lavsund and Sandegren 1991), Beckmann et al. (2010) suggested these reductions may be a result of animals spending less time near the roadways because of the increased lighting and vegetation removal. In urban areas, there is often already considerable lighting along roads, so increasing it may not be an option, although roads through urban open space may be less well-lit, and increased roadway light can have other disadvantages for wildlife (see Sect. 15.2.3.1.4). Vegetation removal will also often occur near urban roads if there are residential or other with specific landscaping needs nearby.

15.4.2.2 Modifying Animal Behavior: Wildlife Fencing and Vegetation

Some mitigation methods directed at modifying animal behavior include reducing the attractiveness of the road or roadside for animals. One way this is accomplished is by removing carcasses from roadways so that carnivores and scavengers, both mammalian and avian, are not attracted to them. Planting unpalatable vegetation along roads may help reduce the attractiveness of roadsides to herbivores (Forman et al. 2003). Habitat alterations and maintaining natural vegetation in movement corridors leading up to a wildlife crossing structure are important to guide safe passage for many species. Vegetation enhances the effectiveness of the wildlife crossing by reducing the distance animals must travel between areas of natural habitat on either side of the road. It also provides cover and minimizes light and noise disturbance (Ruediger and DiGiorgio 2007). Restoring and vegetating the approaches to a wildlife crossing may be especially important in urban landscapes where human development may be close to the corridor on one or both sides, making its use by wildlife less likely (see Fig. 15.3). Although this can be hard to demonstrate conclusively, it is likely much more effective if natural corridors are wide as they lead away from the road to natural areas.

Wildlife-proof fencing is a common mitigation method used throughout the world to keep animals off roadways, ungulates in particular, because of concerns for motorist safety. These fences typically are 1.8 to 3.0 m high and consist of galvanized chain link or wire mesh fence material. Sometimes fences are buried into the ground approximately 0.6 m to keep animals from digging under them. A number of studies have found that wildlife-proof fencing can reduce ungulate–vehicle collisions (e.g., Ward 1982; Ludwig and Bremicker 1983; Dodd et al. 2007; McCollister and van Manen 2010). In Banff National Park, Clevenger et al. (2001b) reported an 80 % reduction in ungulate–vehicle collisions after a wildlife-proof fence was constructed along the Trans-Canada highway. A species-specific fence was developed for European wildcats (*Felis silvestris*) along a motorway in southwestern Germany, which reduced road mortality by 83 % (Klar et al. 2009). Tall fences can act as a barrier for medium-sized mammals as well as ungulates, and smaller mesh added to the bottom of a tall fence can be effective in keeping small mammals, amphibians, and reptiles from entering the roadway. Barrier walls along roads located in wetland systems can also be effective in reducing road mortality of reptiles and amphibians.

Where fencing is used for large mammals, escape ramps (jump-outs) or one-way gates will allow animals that become trapped inside the fencing, after finding their way over, under, or around the fence, to escape. For lower profile mammals such as badgers, small hinged doors at ground level can allow safe escape from the road ROW (Clevenger and Huijser 2010). In one study, earthen escape ramps were shown to be 6–12 times more effective than one-way gates in allowing deer to escape the ROW (Bissonette and Hammer 2000). Deer and elk most frequently use escape ramps, but bighorn sheep (*Ovis canadensis*), bears (*Ursus spp*.), moose, and mountain lions have been reported to use them as well (Clevenger and Huijser 2010).

There is no reason why wildlife-proof fencing will not also be effective in urban areas. It may be more difficult to install in urban settings, because there is often private land or residential or commercial areas abutting the road, making consistent application of the fencing difficult. For larger roads with a mandated ROW, road agencies may be able to dictate whether there is fencing and what kind it is. In California, state roads owned by Caltrans are mandated to have a fence along their ROW, although these fences are not always maintained, leading to holes or gaps. Another problem is that the ROW line may often veer far from the road, leading to significant areas of natural vegetation between the fence and the road, which is an attraction for wildlife. In one project in southern California, after replacing an old, unmaintained fence with a new wildlife-proof one, road mortality for coyotes was reduced by 88 % between the 3 years before the new fence and the 2 years after it (Sikich and Riley 2012).

15.4.2.3 Wildlife Fencing and Crossing Structures

The use of properly designed fencing (with wildlife escape mechanisms) or barrier walls in combination with carefully planned wildlife crossing structures will help reduce wildlife road mortalities and maintain habitat connectivity for a variety of species (Forman et al. 2003; Glista et al. 2009). This has been documented in many different places for large range of species, including in Australia for multiple marsupials, reptiles, and amphibians (Taylor and Goldingay 2003); in Florida both at Paynes Prairie for a range of vertebrates, especially snakes (Dodd et al. 2004), and on Big Pine Key with endangered Key deer (Braden et al. 2008); and in Arizona with elk (Dodd et al. 2007).

Further work is needed to understand how the dynamics of human-dominated landscapes influence wildlife use of crossing structures, but thoughtful application of this combination strategy is likely to be as effective in urban areas as elsewhere. In two studies in urban regions of southern California, we found that mitigation efforts, including clearing out existing underpasses, constructing wildlife-proof fencing, and installing one-way gates in one case (Sikich and Riley 2012), and adding wildlife fencing and modifying a system of existing culverts in another (Boydston and Crooks 2013), were effective in increasing culvert use and reducing road mortality for medium-sized mammals such as coyotes and bobcats.

15.5 Future Directions

Cities have large numbers of people moving across the landscape, and the transportation infrastructure associated with the massive daily migrations of cars runs counter to wildlife needs. Clearly further research is needed to understand: (1) wildlife responses to roads in urban environments; (2) how to modify existing roads; and (3) how to plan for urban expansion that will allow wildlife to also move through these highly fragmented landscapes. Some wildlife responses to roads may scale with road size, traffic volume, and the size of habitat fragments, whether the landscape is a city or a remote natural area. Other responses may be influenced by factors or interactions of factors that are unique to roads in cities, and identifying these interactions is an important step towards effective mitigation. Certain taxa have received more attention than others in road ecology research, with the bulk of the emphasis to date on carnivores and ungulates. While providing connectivity for these larger, wide-ranging mammals may serve a number of smaller animal species, much of the biodiversity in urban areas may require additional or other mitigation strategies along roads to persist. After conducting a meta-analysis using data from 75 studies, Rytwinski and Fahrig (2012) found that amphibians and reptiles, wide-ranging birds and large mammals, and species that do not avoid roads were particularly susceptible to road mortality.

To accommodate urban growth, cities frequently modify their transportation networks. These changes may often include widening of roads for greater carrying capacity of vehicles which can remove wildlife habitat. However, such changes also present opportunities to insert mitigation for wildlife, and in fact, improvements for wildlife that are incorporated into projects that have other goals (e.g., adding a carpool lane) may be relatively low-cost compared to a new wildlife bridge or other expensive mitigation.

Wildlife friendly improvement of roads in urban areas may require extensive funding, but improvements for wildlife may improve urban quality of life for humans beyond the ecosystem services of intact, connected natural areas. For example, planning for wildlife to safely cross roads may also help a city interested in creating friendlier passages for pedestrians and bicycles across freeways. While automotive demands will likely continue to increase for many years, the future of urban transportation planning may include an increased emphasis on public transportation networks such as rail lines and the incorporation of new technologies. Transportation alternatives that can move more people with less use of fossil fuels and lower emissions than cars may present new challenges for wildlife and make for even more complex equations in balancing environmental costs and benefits for wildlife and people. However, working towards improvements for wildlife now will increase the chances that wildlife can be part of the equation in the future.

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