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Estimating annual vertebrate mortality on roads at Saguaro National Park, Arizona

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***Abstract*:** Road-killed vertebrates are a conspicuous effect of roads on animals, particularly in natural preserves where wildlife is protected. Knowledge of the number of vertebrates killed by vehicles in a national park or other natural area is important for managers, but these numbers are difficult to estimate because such mortality patterns vary greatly in space and time and by taxonomic group. Additionally, animals killed by vehicles may be difficult to observe, particularly during driving surveys, and carcasses may not persist between surveys due to scavenging and other factors. We modified an estimator previously developed for determining bird mortality at wind turbines to estimate the average annual number of vertebrates killed by cars on roads within and along the boundary of Saguaro National Park, Tucson, Arizona. Our model incorporates estimates of carcass (hereafter, roadkill) persistence and detectability (determined, respectively, by conducting surveys on 8 consecutive days and by comparing simultaneous walking and driving surveys) with data from regular roadkill surveys conducted throughout the park over a 6-year period. Using this model, we estimated that an average of 29,377 (SE 6,807) vertebrates (approximately 1.1/km/day; SE 0.24) were killed annually during 1994 to 1999 on 76.6 km of roads associated with the park. The majority of killed animals were amphibians and small reptiles, but birds and mammals also were killed in large numbers. The amount of wildlife killed in and near reserves by vehicles may be higher than appreciated by many managers and should be factored into within-park and regional transportation planning.

***Key words*:** human–wildlife conflicts, national parks, road effects, roadkill, vertebrate mortality, wildlife management, wildlife–vehicle mortality

It is well-documented that roads directly and indirectly impact natural resources and systems at many spatial and temporal scales (Andrews 1990, Spellerberg 1998, Trombulak and Frissell 2000, Forman et al. 2003). The extent of these impacts on the environment and local animal populations depends on the characteristics of the road or road network (e.g., road density, route and surfacing, and traffic volume, pattern, and speed), and the site (e.g., topography, weather, hydrology, vegetation, and local wildlife populations and their natural history), but they can be significant and cumulative (Vos and Chardon 1998, Findley and Bourdages 2000, Forman and Deblinger 2000, Carr and Fahrig 2001). If a road lies in or adjacent to a national park or other protected natural area, any impacts are inherently significant because protection and preservation of natural resources is central in these areas (Forman et al. 2003, National Park Service [NPS] 2006, Ament et al. 2008). However, roads are often desirable in protected natural areas to provide access to visitors and administrators, as well as for the scenic views they offer. The dilemma of roads in nature reserves can be a contentious management issue (Pienaar 1968, Bush et al. 1991, Quin 1997, Ament et al. 2008).

One of the most conspicuous of all the impacts of roads, especially in protected areas, is wildlife mortality resulting from collisions with vehicles, or roadkill. Roadkill is undoubtedly the greatest anthropogenic source of direct mortality for vertebrate wildlife in many parks and preserves in the United States, and studies confirm that populations of some species are negatively impacted, even to the point of extirpation, by roadkill (Fahrig et al. 1995; Trombulak and Frissell 2000; Gibbs and Shriver 2002, 2005; Forman et al. 2003). Quantifying roadkill numbers and patterns is important for designing and funding effective mitigation of

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road effects, but it is logistically and analytically difficult due to the high temporal variability and low detectability of roadkills (Smith and Dodd 2003, Dodd et al. 2004).

At Saguaro National Park (SNP) in southeastern Arizona, USA, park managers long have been concerned with the impacts of roads on natural resources, particularly wildlife (National Park Service 1988). The park consists of 2 separate districts: the Tucson Mountain District (TMD; 9,730 ha) and the Rincon Mountain District (RMD; 27,230 ha). The districts are located on opposite sides of Tucson, Arizona, which is one of the most rapidly-growing cities in the United States. The current population of the Tucson metropolitan area is about 1,000,000, >20× the size it was when SNP (then a national monument) was establish-ed in 1933 (U.S. Presidential Proclamation 2032). Like many national parks located near growing urban areas, roadways at SNP (consisting of through-ways, boundary roads, and scenic loop roads) have received steadily-increasing use by visitors and commuters in recent years. During the study period, traffic on the sections of 2 county roads that run through the TMD was about 6,000 and 2,200 vehicles per day and 2,400 vehicles per day on a county road adjacent to the west boundary of the RMD (Pima Association of Governments 2008). By 2006, respective traffic rates on these roads had increased to 7,700, 3,800, and 3,200 vehicles per day. Although this volume of traffic is considered relatively light (Fahrig et al. 1995, Forman et al. 2003), it is well above rates shown to negatively impact land turtles and many amphibian populations (Van Gelder 1973; Hels and Buchwald 2001; Gibbs and Shriver 2002, 2005). These figures approach or exceed the 4,000 vehicle-per-day threshold that Ruediger et al. (1999) conjectured would cause significant impacts to wildlife overall.

Many studies have reported the number of animals killed on specific roads, but there is little quantitative information available on the impact of an entire network of roads on local wildlife in a protected area. To quantify the impacts of roads on wildlife in SNP, park staff began collecting roadkill data on their regular (i.e., approximately weekly) driving surveys during 1994 (Kline and Swann 1997, 1998). Although this methodology is commonly used to quantify roadkill (Rosen and Lowe 1994, Drews 1995, Fahrig et al. 1995, Mallick et al. 1998), it is insufficient to detect the true number of animals killed because many individual carcasses are not seen by observers in moving vehicles. Other carcasses disappear from the road between surveys (Kline and Swann 1997, 1998; Hels and Buchwald 2001; Smith and Dodd 2003; Dodd et al. 2004). During initial surveys at SNP, it was apparent that many variables affected both the number and species of animals killed on roads throughout the year, as well as the ability of observers to detect them (Kline and Swann 1997, 1998). Therefore, we designed additional surveys to determine roadkill persistence (average carcass residency time), and roadkill detectability from automobile surveys. Using these 3 independent data sets and a standard estimator developed to estimate avian mortality caused by wind turbines (Schoenfeld 2004), we estimated the average annual number of roadkills in the park by taxonomic class, district, and season.

Methods

Roadkill surveys

We surveyed all roads in and adjacent to SNP (76.6 km) during January 1994 to December 1999. A trained biology technician drove the entire network of roads in each district (43.9 km in the TMD; 32.7 km in the RMD) approximately once each week. We surveyed for 3 years (1994 to 1996) in the TMD and 4 years (1996 to 1999) in the RMD. We conducted 110 roadkill surveys in the TMD and 160 in the RMD; mean interval between surveys was 8.8 days in RMD and 9.5 days in TMD. We usually surveyed from 0830 and 1200 hours, followed a standard route, and drove a light truck at speeds of approximately 24 km/hr to 40 km/hr. We stopped the vehicle and identified individual carcasses to species level when possible, but to genus, family, order, or even class, if poor specimen quality made more specific identification impossible. We noted roadkills recorded on previous surveys (i.e., >1 week old; generally parts of large mammals) but did not record them as data. Initially we recorded carcass locations by general road section, then (after 1997) to the nearest 0.16 km on a given road.

Roadkill persistence

To estimate average persistence time of

roadkills, we conducted morning (i.e., 0800 to 1100 hours) surveys on a 3.5-km section of road along the northern boundary of the RMD each day for 8 consecutive days during the summer rainy season in 1999. On the first day, we scraped off the road and discarded any animals that we were not absolutely certain had been killed during the previous 12 hours. We marked all remaining carcasses by placing a pin flag off the shoulder of the road immediately adjacent to the carcass. On subsequent days, we recorded the fate of all previously marked carcasses and marked any new individuals.

The maximum likelihood estimator for the mean residency time with right-censored data (some carcasses were still resident at the study's end) is

$$\bar{t} = \sum t_i / (n - n_c) \qquad (1)$$

where t_i is the observed residency time of carcass i, n is the sample size, and n_c is the number of carcasses that were still present at the end of the study. There is no closed-form standard error formula for this estimator, so we estimated the standard error using a bootstrap approach (Efron and Tibshirani 1986). The data set comprised 95 carcasses; for each of these, we recorded the residency time and whether it was still present at the end of the study (i.e., censored). We randomly sampled with replacement 1,000 times from this data set, each time generating a bootstrapped estimate. The bootstrap SE is the standard deviation among these re-sampled estimates.

Roadkill detectability

Observers counting carcasses while driving the road network failed to detect some of the roadkills present for many reasons. To account and correct for these missed carcasses, we devised a study to estimate the detection probability for our system. We estimated the observer's roadkill detection rate by comparing the number of carcasses recorded during a driving survey to the number seen during concurrent walking surveys of the same areas. We conducted 7 walking, or ground-truthing, surveys (i.e., 4 in the RMD; 3 in the TMD) where 2 to 4 volunteer technicians surveyed each road in the district, while a regular driving survey was simultaneously conducted by a trained biology technician. We treated this as a binomial process, so the estimated detection rate (for taxon t) is

$$\hat{p}_t = \frac{n_{d,t}}{n_{w,t}}; \left(SE = \sqrt{\frac{\hat{p}_t(1-\hat{p}_t)}{n_{w,t}}} \right) \qquad (2)$$

where $n_{w,t}$ is the number of carcasses of taxon t detected by walkers, and $n_{d,t}$ the number detected by drivers.

Roadkill estimates

We estimated roadkill numbers for each of 4 vertebrate classes (amphibians, birds, mammals, and reptiles), for each district of the park (RMD and TMD), and for each of 2 strata (i.e., seasons; monsoon and non-monsoon). We defined the monsoon season as July to October and treated these data separately from non-monsoon data because it is the time of year when, by far, the most vertebrates (i.e., individual animals, as well as taxa) are active in the Sonoran desert. To calculate roadkill numbers from our regular survey data, we modified an estimator developed by Shoenfeld (2004) to estimate avian mortality in the wind turbine industry. The issues regarding the estimation of vertebrate mortality from wind turbines parallel very tightly those encountered in the current situation. Carcass counts are made at regular (i.e., often weekly) intervals; carcasses may be removed by scavengers or other mechanisms without being detected (i.e., carcass residency time), and surveyors cannot reliably detect all the carcasses generated (i.e., detection rate). Thus, the methodology developed for the wind turbine issue applies with little change to the road-mortality issue.

The estimator is

$$\hat{M} = \left(\frac{C}{n\bar{I}} \right) \left(1 + \frac{\bar{I}}{\bar{t}\hat{p}} \right) S \qquad (3)$$

where $\hat{M}$ is the estimated mortality; C is the number of carcasses seen over all surveys that occurred during the relevant season; n is the number of such surveys; $\bar{I}$ is the average interval between surveys; $\bar{t}$ is the mean carcass residency time; $\hat{p}$ is the detection rate; and S is the number of days in the relevant season. Thus, omitting subscripts for ease of reading formulae, for a single taxon during 1 season in 1 district, the estimated number of roadkills that would be seen as

$$\left(\frac{C}{n\bar{I}}\right)S \tag{4}$$

while

$$\left(\frac{C}{n\bar{I}}\right)\left(\frac{I}{\bar{t}\hat{p}}\right) \tag{5}$$

corrects for roadkills where the carcass was gone by the survey day (i.e., roadkill persistence), and for roadkill detectability. The estimator does not have a closed form SE, so we estimated that (and produced confidence intervals) by bootstrapping. Annual estimates for each taxon (and for all taxa combined) in each district and for the park overall were calculated by summing the monsoon and non-monsoon estimates.

Results

Roadkill surveys

In all, we observed 2,023 vertebrates killed on roads and identified them to taxonomic class as amphibian (e.g., toads [*Bufo* spp.] and spadefoot [*Scaphiopus couchii*]), reptile, bird, or mammal. In addition, we categorized and recorded 215 individual road-killed animals as unknown, but we did not include these in further analysis. In September 1996, a single survey at TMD recorded 279 amphibian roadkills, a far greater number than observed on any other survey. We included these results because we have observed incidentally many similar episodic mass-mortality events and believe that the datum is not anomalous.

Roadkill persistence

During the 8-day persistence survey, we marked a total of 95 carcasses, the majority of them amphibians. Small sample sizes for non-amphibian roadkills prevented taxonomic-specific analysis of these data. We estimated mean carcass residency time for all taxonomic groups combined to be 3.2 (SE 0.3) days.

Roadkill detectability

During 7 surveys, we compared the results of driving and walking surveys on the same route; walkers observed 1,286 individual vertebrate roadkills, while drivers observed 83 (6.5%, SE 0.7%). Drivers detected 39 of 808 amphibian roadkills observed by walkers (4.8% SE 0.8%), 11 of 294 (3.7% SE 1.1%) reptiles, 20 of 58 (34.5% SE 6.2%) birds, and 13 of 126 (10.3% SE 2.7%) mammals. We calculated an SE for each taxa by treating the estimates as binomial proportions (Ramsey and Shafer 2002). Our estimated detection rates differed sufficiently among taxa for us to calculate taxon-specific correction factors.

Roadkill estimates

We estimated seasonal and annual numbers of individual animals killed by motor vehicles for each taxon in each district (Table 1). We estimate that 20,599 (SE 6,601) vertebrates are killed annually at TMD and 8,778 (SE 1,664) at RMD, for an estimated 29,377 (SE 6,807) on the 76.6 km of roads that run through or along the boundaries of SNP (i.e., 1.05 roadkills per km per day; SE 0.24). During the monsoon season, the park averaged 2.4 vertebrate roadkills per km per day (SE 0.7), or about 6.5× more than during the non-monsoon season (i.e., 0.4 roadkills per km per day; SE 0.1).

Discussion

Roadkill persistence

The amount of time that individual carcasses persist on the road depends on many factors. Our observations suggest that scavenging by birds, mammals, and insects are the primary reasons for roadkill disappearance, but some small vertebrates simply disappear because they are flattened by cars and carried away by wind or water. We also observed roadkills, generally larger animals (i.e., rattlesnakes and raptors) being removed from the road by humans.

Few studies have evaluated the persistence of roadkills on roads. Hels and Buchwald (2001) found that 7 to 67% (i.e., approximately 13% overall) of amphibians observed killed on roads during a 24-hour period were detected during daily walking surveys. Smith and Dodd (2003) employed a mark-recapture technique similar to our carcass persistence methods to estimate the average vertebrate kill-rate per day within 1 year. Although they acknowledged scavenging and other reasons for the disappearance of

Table 1. Average seasonal and annual estimates of numbers of animals (for each of 4 taxa) killed by vehicles on the roads of Saguaro National Park, 1994–1999.

Taxon	Season	TMD[a]	RMD[b]	Parkwide
Mammals	Monsoon	1,561 (568)	818 (307)	2,379 (646)
	Non-monsoon	1,066 (400)	701 (265)	1,767 (480)
	Annual	2,627 (695)	1,519 (406)	4,146 (804)
Birds	Monsoon	119 (35)	173 (44)	292 (56)
	Non-monsoon	224 (59)	242 (62)	467 (86)
	Annual	343 (69)	415 (76)	759 (102)
Reptiles	Monsoon	5,921 (2,815)	1,734 (781)	7,655 (2,921)
	Non-monsoon	2,882 (1,526)	1,727 (804)	4,609 (1,725)
	Annual	8,803 (3,202)	3,461 (1,121)	12,264 (3393)
Amphibians[c]	Monsoon	8,826 (5,730)	3,382 (1,158)	12,208 (5,846)
All taxa combined	Monsoon	16,427 (6,409)	6,107 (1,431)	22,534 (6,567)
	Non-monsoon	4,172 (1,579)	2,671 (849)	6,843 (1,792)
	Annual	20,599 (6,601)	8,778 (1,664)	29,377 (6,807)

[a]Tucson Mountain District of Saguaro National Park.
[b]Rincon Mountain District of Saguaro National Park.
[c]Amphibians are active only during the monsoon season (July–October).

roadkills, they did not attempt to calculate or otherwise take into account roadkill persistence. They did note that roadkill detections increased with increasing survey effort (Smith and Dodd 2003), so any estimates of roadkill must account for carcass persistence in order to avoid gross underestimation (Hels and Buchwald 2001).

Roadkill detectability

We are not aware of other studies that have directly compared driving surveys with walking surveys, although at least 1 study (Langen et al. 2007) makes indirect comparisons. The detectability of road-killed animals during driving surveys was surprisingly low, and there was markedly different detectability among taxonomic groups. Overall, if we assume that all roadkills were detected by walkers (see roadkill estimates section below), only 6.45% (SE 0.7%) of vertebrate roadkills were detected by drivers. Generally, amphibians (e.g., toads) and small reptiles, particularly lizards, were less detectable to drivers, whereas, larger mammals, snakes, and birds were more consistently detected. Although most recent studies, particularly of amphibians, have recognized that surveys must be conducted on foot to ensure adequate detection of roadkills (Ashley and Robinson 1996; Hels and Buchwald 2001; Gibbs and Shriver 2005; Langen et al. 2007, 2009), many other roadkill studies (Bernardino and Dalrymple 1992, Rosen and Lowe 1994, Mallick et al. 1998, Glista et al. 2008) have conducted surveys using observers in motor vehicles. Our data suggest that the inability of drivers to see small vertebrates is far greater than most drivers realize.

Our study assumed that all roadkills were detected by walking surveyors, but this assumption is certainly not always valid; an unknown number of animals, notably birds and large mammals that collide with the vehicle itself (i.e., car body versus being crushed by the wheel), are thrown off the roadway entirely, and surveyors frequently miss them. Walking surveyors in our study detected by smell several such carcasses (usually large mammals) in vegetation off the road shoulder, but we presume that even during walking surveys many roadkills, birds in particular, will remain undetected. Obtaining an absolute detection rate for animals thrown from the road would be difficult, but this parameter could be estimated by a separate study that systematically surveyed for roadkill beyond road shoulders. Many more animals are probably hit by cars and die well away from the road, maybe even days later. These animals are particularly difficult to count, ensuring that the count of wildlife killed on roads will tend to be underestimated.

Roadkill estimates

Many studies suggest that wildlife mortality from vehicles is a problem in protected areas and likely impacts animal populations negatively (Pienaar 1968, Bernardino and Dalrymple 1992, Drews 1995, Vos and Chardon 1998). Few studies, however, have attempted to quantify the total number of vertebrate roadkills for an entire road network in a park or natural area. Ashley and Robinson (1996), Smith and Dodd (2003), and Dodd et al. (2004) quantified the number of roadkills along particular roads where roadkill was perceived to be an issue in a protected area. Ashley and Robinson (1996) reported an average of 12.61 vertebrates per km per day during the months of April through October on the Long Point Causeway adjacent to the Big Creek National Wildlife Area in Ontario, Canada. Total observed mortality for their seasonal 4-year study exceeded 32,000 vertebrates. Although they acknowledged the issue, carcass persistence was not accounted for. Smith and Dodd (2003) estimated vertebrate mortality at 5.4 km per day on 3.2 km of U.S. Highway 441 where it passes through Payne's Prairie State Park in Florida. This number, multiplied by 3.2 km and 365 days per year provided their estimate of 6,314 roadkills annually. Hels and Buchwald (2001) studied a 600-m stretch of road in Denmark during the amphibian breeding season and estimated that between 797 and 1,366 amphibians were killed in 1 year, and between 308 and 551 amphibians were killed in another year. Their estimates ranged from 3.6 to 16.1 amphibian killed per km per day. All of these estimates exceeded our estimate of 1.1 roadkills per km per day.

Variation in the innumerable factors (e.g., methods used to quantify roadkill, weather, traffic volume and pattern, local animal populations, etc.) that account for the number of vertebrates killed by vehicles on roads, even at a given site on a given road make such comparisons between sites, and sometimes even within a site between years, difficult to interpret. Nevertheless, trends in roadkill numbers obtained from systematic surveys over time can be very informative, especially when knowledge of local wildlife populations can provide context for interpreting such results.

Of the 2 factors we studied, roadkill persistence and detectability, that affected our ability to count roadkills accurately on our regular driving surveys, the most important factor influencing the size of our estimates was the inability of drivers to see roadkills. We conducted driving and concurrent walking surveys during the rainy summer period in Arizona when roadkill sample sizes are largest. We are not aware of any factors (e.g., lighting differences, traffic differences) that would have caused roadkill detectability to differ among seasons, but it is possible that persistence might vary among seasons based on differences in scavenger activity and weather; for example, carcasses might decompose more rapidly during summer.

The numbers of roadkills that we and others reported are higher than many drivers and park managers might expect. This is because most animals killed by cars are too small to be seen from vehicles traveling at even a moderate speed. Many toads, lizards, and small snakes and rodents probably go undetected by drivers even when they are alive, but as soon as they are killed and flattened they become very difficult to see.

Management implications

Many recent studies have demonstrated the impacts that America's extensive road network has on natural resources, including wildlife (Forman et al. 2003). For natural areas such as national parks, the problem is particularly acute because agencies, such as the National Park Service, are responsible both for providing opportunities for visitors to enjoy natural resources and protecting these resources *in situ* for future generations. Moreover, many protected areas like SNP are increasingly surrounded by urbanization, including residential neighborhoods where the proximity of a park is a major attraction. Thus, roads are used by visitors enjoying the park, as well as by park neighbors who commute to work or drive through the park to accomplish other routine tasks.

Figure 1. Saguaro National Park and Pima County, Arizona, collaborated to design and construct a wildlife-friendly culvert on Sandario Road adjacent to the park. (*Photo courtesy National Park Service*)

Loss of species from national parks due to road impacts may be difficult to prevent, given Americans' predilection to motor vehicles. In addition, many roadkills at Saguaro occur on roads adjacent to the park that are not administered by NPS. Regardless of cause or magnitude, however, this impact is inconsistent with the mission of the NPS to preserve wildlife for future generations and with current policies that discourage the destruction of animals in parks unless there is a compelling management purpose (NPS 2006). In a recent survey of 109 NPS managers, Ament et al. (2008) reported that >50% of respondents indicated that they believed roads were negatively affecting animal populations and that the problem would worsen during the next 5 years. Our study did not attempt to link the numbers of roadkills to impacts on wildlife populations, but other studies have made this connection (Van Gelder 1973; Carr and Fahrig 2001; Gibbs and Shriver 2002, 2005; Harveson et al. 2004). Bangs et al. (1989), Rosen and Lowe (1994), Jones (2000), and Mumme et al. (2000) report negative impacts, and even local extinctions, to populations of certain species of mammals, birds and reptiles resulting from roadkill in protected natural areas. Roadkill is most likely to impact the populations of rare, or long-lived species with low reproductive output (Bonnet et al. 1999).

Our results demonstrate that, by any measure, mortality due to motor vehicles greatly exceeds many known threats to animals in parks and may be comparable to very large-scale impacts caused by water diversions (Johnson and Caruthers 1987), extensive habitat loss outside parks (Newmark 1995, Powell et al. 2005), and invasive species (Johnson and Caruthers 1987, McCann and Garcelon 2008). An approach for future road management in national parks would be to require that all new roads, if they are deemed absolutely necessary, strive for an ideal of no animal mortality through use of currently available and emerging technologies (e.g., overpasses, underpasses [Figure 1], and fencing; U.S. Department of Transportation 2000, Forman et al. 2003, Glista et al. 2009). Mitigation measures have up-front costs, but they may be small compared to the indirect but cumulative cost of not protecting wildlife from roadkill in protected natural areas, especially when the overall number of such refugia may be declining. Additionally, parks will be well-served by working closely with regional transportation planners to reduce road densities or to retrofit and upgrade existing roads in areas adjacent to parks where wildlife mortality is likely to be high.

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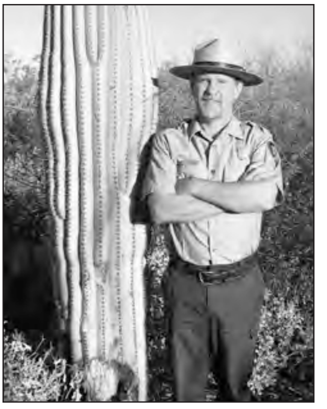

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