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Authors

Waller, John S.
Servheen, Christopher
Patterson, David A.

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PROBABILISTIC MEASURE OF ROAD LETHALITY

John S. Waller (Phone: 406-888-7829, Email: john_waller@nps.gov), Glacier National Park, West Glacier, MT 59936, Fax: 406-888-7946

Christopher Servheen (Phone: 406-243-4903, Email: grizz@umontana.edu), U.S. Fish and Wildlife Service, College of Forestry and Conservation, University Hall, Room 309, University of Montana, Missoula, MT 59812

David A. Patterson, Department of Mathematics, University of Montana, Missoula, MT 59812

Abstract: Throughout the world, the effects of highways and railroads on wildlife have been of great concern to scientists, land and wildlife managers, and the public, for over 80 years. Through these years, many researchers have sought to understand and mitigate the negative impacts of roads through theoretical and empirical research. However, to our knowledge, no one has investigated the underlying probability theory that likely governs the extent to which linear transportation features result in wildlife mortality. One reason may be that the number of factors potentially influencing observed patterns of road mortality can be quite large and can quickly become intractable. Our objective here was to suggest that the lethality of linear transportation features to wildlife is governed primarily by two factors: traffic volume and time spent on the roadway. Using a simple Poisson model of expected vehicle arrival times, we estimated the probabilities of animals successfully crossing roads under different traffic volume and animal mobility constraints. We used actual vehicle counts from two study areas as examples, and used a study of grizzly bears along a major railroad and highway to illustrate these concepts. We discuss the usefulness of this approach to conservation problems, and place it in context with other efforts to quantify the occurrence of wildlife mortality due to highways. Our hope is that these ideas will clarify and advance the search for solutions to what previously has been an intractable problem.

Introduction

Throughout the world, the effects of highways and railroads on wildlife have been of great concern to scientists, land managers, and the public (Forman 2000). The automobile has long been recognized as a causal agent of mortality, and efforts to quantify this mortality go back over 80 years (Stoner 1925). Many investigators have continued these efforts through the years (Davis 1934, Dickerson 1939, Bellis and Graves 1971, Garland and Bradley 1984, Clevenger et al. 2003). More recent theoretical developments in island biogeography and landscape ecology have increased concern about maintaining connectivity within and between wildlife populations (MacArthur and Wilson 1967, Forman 1995). Theoretical and empirical research shows that highways and railroads can fragment wildlife habitats, with potentially negative consequences (Noss et al. 1996). Numerous studies have quantified the movement patterns of wildlife across linear transportation features (e.g., Foster and Humphrey 1995, Hewitt et al. 1998, Gibeau 2000). However, to our knowledge, no one has investigated the underlying probability theory that likely governs the extent to which linear transportation features result in wildlife mortality.

One reason may be that the number of factors potentially influencing observed patterns of road mortality can be quite large. Possible factors include those unique to species, such as mobility, food preferences, and behavior. They may also include factors relating to population status, including density, age structure, sex ratio, and cyclic patterns of reproduction and movement. Other factors may be related to habitat, such as spatial positioning of crucial resources like water or breeding areas, or seasonal changes in climate, presence of attractants, or occurrence of flood, fire, and drought. Still more factors apply to the linear feature itself, including type (railroad, two-lane road, four-lane divided highway), design (width, tortuosity, grade), and capacity (speed and volume). Also affecting mortality are elements of driver behavior (attentiveness, reaction time) and vehicle type (large truck or passenger car). The list of confounding factors may be limited only by imagination.

Our objective here is to suggest that the risk that linear transportation features pose to wildlife is governed primarily by two factors: traffic volume and time spent on the roadway by wildlife. Roadkill often occurs when vehicles and animals attempt to occupy the same space at the same time. Most of the factors listed above might affect if or when an animal decides to cross a road, but once the animal begins crossing, largely deterministic processes take over. We used a study of grizzly bears along a heavily used railroad and highway to illustrate the usefulness of this approach.

Methods

Traffic engineers have developed a rich body of theory to describe traffic pattern and flow (Garber and Hoel 1999, Troutbeck and Brilon 2002). Gap-acceptance theory has been developed to allow highway engineers to quantify the process of vehicles from minor traffic streams merging into major streams. Usually, drivers will not merge unless there is a gap in traffic sufficient to accommodate their own vehicle – the critical gap. The occurrence of gaps in traffic greater than or equal to the critical gap depends on the arrival times of vehicles at the area of intersection. Numerous models have been proposed to describe the patterns of vehicle arrival at intersections, but for light to medium traffic volumes, the Poisson model is often used (Garber and Hoel 1999:205). In the Poisson model, vehicles are assumed

to arrive at random times independently of each other. The number of arrivals in any interval of length t seconds has a Poisson distribution with mean μ = average number of arrivals per t seconds. That is, the probability of x arrivals during any interval of t seconds is

$$P(x|t) = \mu^x e^{-\mu} / x!, \quad x = 0, 1, 2, \dots \quad (1)$$

Since $\mu = \lambda t$, where λ is the mean number of arrivals per second, we can rewrite equation (1) as

$$P(x|t) = (\lambda t)^x e^{-\lambda t} / x! \quad (2)$$

Let T be the number of seconds from any point in time until the next vehicle arrival. Then, by equation (2),

$$P(T > t) = P(\text{no arrivals in next } t \text{ seconds}) = P(0|t) = e^{-\lambda t}, \quad t > 0 \quad (3)$$

and

$$P(T \leq t) = 1 - e^{-\lambda t}, \quad t > 0 \quad (4)$$

that shows that T has an exponential distribution. Note that the time until the next arrival is independent of the time since the last arrival. This is the “memoryless” property of the exponential distribution and the Poisson model. Our interest here is determining the probability of animals successfully crossing a highway. If we assume that the critical gap h is the time (in seconds) necessary to cross one lane of traffic, then, by equation (3), the probability that an animal will successfully cross the lane is

$$P(T > h) = P(0|h) = e^{-\lambda h} \quad (5)$$

where λ is the average number of vehicles per second for one lane. Crossings of multiple traffic lanes are considered independent events, and, therefore, the probabilities are multiplicative. A successful crossing of one lane depends on the traffic volume in that lane and does not influence the success or failure of crossing additional lanes.

The critical gap may vary greatly between and within species. A running deer (*Odocoileus* spp.) may cross a lane of traffic in a fraction of a second, or it may stand spellbound in the traffic lane for many seconds. We displayed the chances of mortality under these varying scenarios by plotting $1 - P(0|h)$ against time (or the critical gap h) for several different values of λ . Therefore, we implicitly assume that roadkill is an instantaneous event uninfluenced by avoidance behaviors of animals or drivers.

The value of λ , the mean number of vehicles per second, is estimated from observed traffic counts as V/S , where V is the total number of vehicles observed over S seconds. The value of λ will vary over the course of a day, week, or year. Separate estimates may be necessary for different times during the day and different times of year. For example, if animals are crossing primarily during low-volume periods, using an average volume over time periods where traffic volume varies considerably will obviously give spurious results. In addition, the estimated probability of a successful crossing from equation (5) using an average value of λ will underestimate the average probability of success averaging over the individual values of λ .

Between 1998 and 2001 we conducted a study examining the highway-crossing behavior of grizzly bears along US Highway 2 (US-2) and a portion of the Burlington-Northern Santa Fe railroad in northwestern Montana (Waller and Servheen, in press). During that study we continuously monitored road and rail traffic volume and direction. We found that grizzly bears crossed US-2 and the railroad primarily at night. Highway traffic volumes were much lower at night than during the day, while railroad traffic volumes were higher at night. We used this traffic volume data in equation (5) to calculate the probability of being struck on US-2 given lane crossing times of 0.3 seconds to 2 minutes. We chose to use lane width to calculate crossing times rather than vehicle width because the former is constant over long stretches of highway, whereas vehicle width varies significantly by vehicle type. Representative observed single-lane traffic volumes on US-2 were 21 vehicles/hr at night during those hours when grizzly bears crossed, 44 vehicles/hr overall, and 89 vehicles/hr during daytime. For comparison, we also calculated the probability of mortality on the Trans-Canada highway in Banff National Park, given a published average daily traffic volume of 25,000 vehicles per day (Gibeau 2001). Lacking more specific data, we assumed that this traffic was distributed evenly over a 24-hr period and across four traffic lanes.

We also used equation (5) to estimate the probabilities of being hit given movement rates representative of differing modes of crossing or species with differing levels of mobility. We chose movement rates of 13.7 m/s, which would approximate that of an ungulate or bear running at top-speed – 4.6 m/s, which approximates a large animal trotting across the road; 1.5 m/s, approximating a large animal walk; and 0.15 m/s, which might represent a very slow-moving species, such as a turtle or snake.

Railroad traffic can be considered in the same manner as highway traffic, but differs in the distribution of arrival times between cars. Railroad cars, when strung together in a train, have exceedingly short gaps between them. The gaps are much shorter than one would observe in all but the heaviest traffic. These short gaps are then followed by much longer gaps between trains. One of the criticisms of using the Poisson distribution to model vehicle gaps is that under heavy-traffic situations it tends to overestimate the number of gaps less than one second (Garber and Hoel 1999). These short gaps generally do not occur in highway traffic due to the tendency of drivers to maintain longer gaps out of concern for safety. However, for train car spacing, gaps less than one second do occur as the rule. Therefore, we have also used the Poisson distribution to model the probability of being struck by a train.

An alternative would be to treat the train as a single vehicle. Such a treatment would implicitly assume that railroad kills occur only as the result of contact between the animal and the leading engine of the train. No empirical data exist on the specific manner in which wildlife are killed by trains, but anecdotal reports suggest that animals are killed while trying to pass underneath moving trains. In many cases, the bottoms of train cars may be 1-1.5 m above the ground due to the height of their wheels. This configuration allows animals to easily see underneath passing trains. Should a passing train separate social animals, such as a herd of ungulates or family group of bears, individuals may attempt to cross under the passing cars. Such occurrences suggest that using an individual car-based approach is appropriate. Treating an entire train as one vehicle would likely underestimate the true probability of mortality. We use records of bears killed on US-2 and the adjacent railroad, as well as other literature, to support our arguments.

Results

Animals crossing US-2 at night have a high chance of crossing successfully, whereas those attempting to cross the Trans-Canada highway have a high probability of dying in the attempt (table 1, figure 1). A recent study of grizzly bear movements along the Trans-Canada highway found that very few grizzly bears attempted to cross (Gibeau 2000). Using an average rail traffic volume of 1.2 75-car trains per hour in equation (5), we calculated that the probability of being hit by a train duplicates the probability of being hit while crossing US-2 during the day. The probability of being struck increases with increasing traffic volume for species having different movement rates (figure 2). Species incapable of moving quickly, or those predisposed to pausing in the roadway, are more likely to be hit.

According to this model, bears crossing the railroad are approximately four times more likely to be hit than those crossing US-2 at night. During our grizzly bear study along US-2, no grizzly bears that we know of were hit on US-2, but three were struck and killed by trains, including two marked study animals. At a larger scale, 13 grizzly bears were killed by trains between West and East Glacier, Montana, during the period 1992-2002, and only two were struck by cars (C. Servheen, unpublished data).

Table 1. Probability of being struck on US-2 or Trans-Canada highway given time on roadway

Seconds in Roadway	% Chance of roadkill – US2, night	% chance of roadkill – US2 average	% chance of roadkill – US2 day	% chance of roadkill - TransCanada
0.333	0.376	0.76374	1.522	9.154
0.667	0.751	1.5216	3.020	17.469
1.000	1.124	2.2737	4.496	25.024
1.333	1.495	3.0201	5.949	31.887
1.667	1.866	3.7607	7.380	38.122
2.000	2.235	4.4958	8.789	43.786
2.333	2.602	5.2252	10.177	48.931
2.667	2.968	5.9490	11.544	53.606
3.000	3.333	6.6673	12.890	57.853
3.333	3.697	7.3801	14.216	61.711
3.667	4.059	8.0875	15.521	65.216
4.000	4.419	8.7894	16.806	68.400
4.333	4.779	9.4860	18.072	71.292
4.667	5.137	10.177	19.319	73.920
5.000	5.493	10.863	20.547	76.307
5.333	5.849	11.544	21.756	78.476
5.667	6.203	12.219	22.946	80.446
6.000	6.555	12.890	24.119	82.236

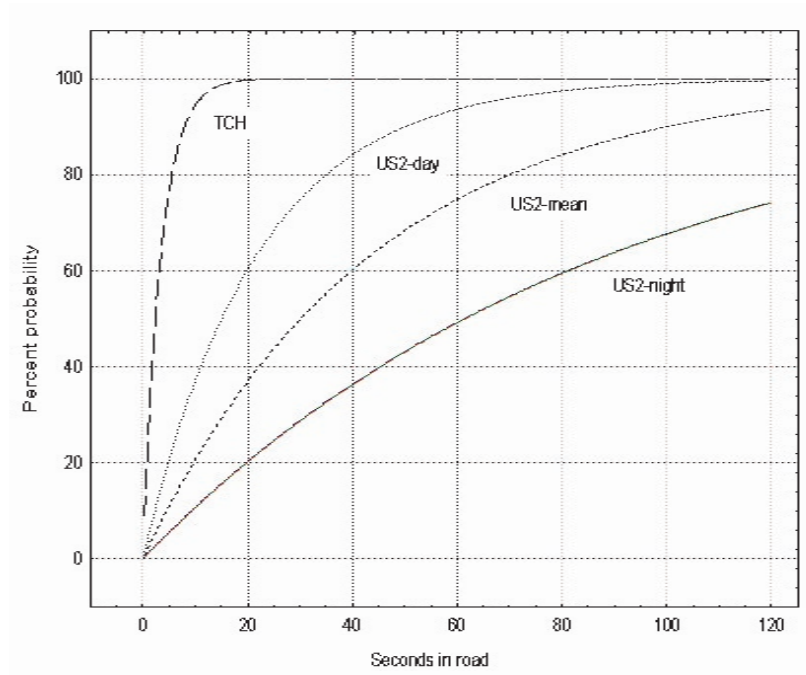


Figure 1. Percent probability of being hit by a vehicle during t seconds in roadway given the following traffic volumes: TransCanada Highway (TCH), 260 vehicles per hour (v/h) * 4 lanes; US-2 daytime, 89 v/h * 2 lanes; US-2 mean, 44 v/h * 2 lanes, US-2 night, 21 v/h * 2 lanes.

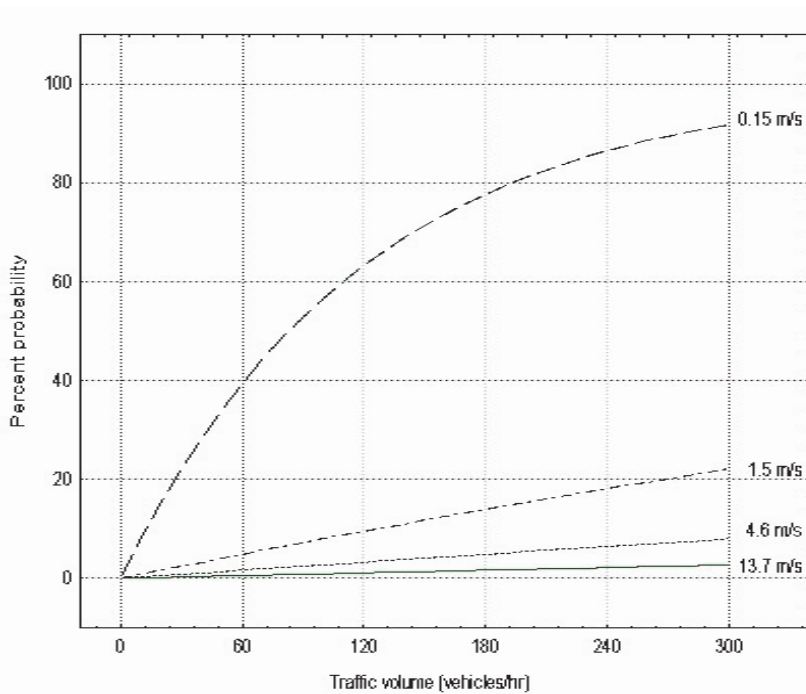


Figure 2. Percent probability of being hit by a vehicle given various traffic volumes (v/h) and movement rates (m/s).

Discussion

Vehicle speed is not a factor in this model; however, speed has never been definitively implicated as a factor leading to higher roadkill rates. Only two studies have directly examined the effect of speed on roadkill rates. Gunther et al. (1998) concluded that speed was the most significant factor affecting roadkill rates in Yellowstone National Park, but he did not measure traffic volume. Bertwistle (1999) studied the effect of vehicle speed on collisions with bighorn sheep and elk in Jasper National Park. He found that reduced speed zones were associated with more collisions with bighorn sheep and fewer with elk. He acknowledged the possible influence of traffic volume, but does not evaluate its role in the frequency of collisions.

Vehicle speed is usually confounded with road capacity. Roads must be designed to accommodate higher vehicle speeds, and such designs often carry higher traffic volumes. Gilbert and Wooding (1996) showed an increasing trend in the number of black bears killed on highways in Florida with concurrent increases in traffic volume on those same highways. Although vehicle speed does not affect arrival time given a governing distribution such as the Poisson, speed may influence the probability of roadkill by limiting the ability of drivers to make evasive maneuvers and by decreasing the time wildlife has to react to approaching vehicles. However, we believe that the influence of speed is small. Roadkill was recognized as a serious problem at a time when vehicle speeds seldom exceeded 40 km/hr (Stoner 1925).

Management Implications

These results allow biologists and highway planners to objectively evaluate the risk of roads and highways to wildlife without having to produce actual records of mortalities. In fact, the risk a particular roadway may pose to any species, extant or not, can be quantitatively assessed. Because this model deals with the instantaneous probability of intersection, it can apply to any species entering the traffic stream. However, use of this model requires qualitative assessment of the speed at which an individual animal may cross each traffic lane. For example, biologists may wish to evaluate the danger of a particular roadway to an endangered species prior to augmentation or reintroduction. For rare, wide-ranging species, such as fisher (*Martes pennanti*), lynx (*Lynx lynx*), wolverine (*Gulo gulo*), wolves (*Canis lupus*), or grizzly bear (*Ursus arctos*), each road mortality may have noticeable demographic effects, yet one may never observe enough road mortalities to make confident decisions concerning risk.

Further, this approach is useful given a wide range of actual traffic distributions. In this paper, we limited discussion to an assumed Poisson distribution of vehicle arrival; however, one can easily document any traffic pattern with empirical data and calculate probabilities associated with successful crossings. Jaeger and Fahrig (2004) recently modeled persistence times of hypothetical populations confronted with fenced and unfenced roadways. Fencing is often considered as a means to mitigate high wildlife mortality, but may increase the barrier effect of the roadway. Jaeger and Fahrig (2004) examined the trade-off between mortality, road avoidance, and movement, and found that at roadkill probability levels of 80 percent or more, fencing increased population persistence. While they caution that their results are qualitative, combining their work with ours allows further exploration of alternative conservation actions.

We stress that readers should not confuse the probability of roadkill with the rate of roadkill. Any of the factors cited above may affect the observed rate of mortality. Species rare or absent along roads are unlikely to be killed on them regardless of traffic volume. Conversely, species congregating along roads due to the presence of an attractant, such as salt, forage, carrion, or spilled grain, may likely be found killed despite low traffic volumes. Observed roadkill results from the interaction of risk (probability) and opportunity.

Biographical Sketches: John S. Waller is the carnivore ecologist at Glacier National Park, Montana. He has specialized in research and management of grizzly bears for 17 years. He holds bachelor and doctoral degrees in wildlife biology from the University of Montana and a master's degree in fish and wildlife management from Montana State University.

Christopher Servheen is the grizzly bear recovery coordinator for the U.S. Fish and Wildlife Service, a position he has held for 25 years.

David A. Patterson is a statistician and professor in the Department of Mathematical Sciences at the University of Montana.

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