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TRAFFIC VOLUME AS A PRIMARY ROAD CHARACTERISTIC IMPACTING WILDLIFE: A TOOL FOR LAND USE AND TRANSPORTATION PLANNING

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Abstract

Based on an analysis of current literature, we developed a Traffic Volume Wildlife Tool that identifies different levels of traffic volume as a means to assess risk to various wildlife species groups, including amphibians, reptiles, birds, and mammals. Each level includes an assessment of when impacts to different species groups begin and when they become a serious threat. Traffic volume, or the amount of traffic using a road, poses substantial negative consequences for many wildlife species, especially as traffic levels increase. Road location and traffic volume are the two most important factors to assess when evaluating a road's potential impacts. Increases in traffic volume alter species composition, impedes animal movement, causes direct mortality, and fragments habitat. Based on the existing studies that quantify traffic volume and measure impacts to wildlife, we developed guidelines for use in planning. We discuss how changes in traffic volume affect habitat quality and animal behavior, and which types of species are most vulnerable. We recommend using these data and guidelines in land use and transportation planning and permitting.

Introduction

Roads play an increasingly important role in both supporting our social and economic welfare and determining the success of our conservation work. Roads enhance human social interactions and contribute to economic development by creating safe and efficient transportation routes for the goods and services we all need and use. They also provide access to jobs, our families, and recreation sites including remote areas.

On the other hand, roads have an enormous impact on wildlife and wildlife habitat. Although direct loss of habitat appears small from a landscape perspective, taking up only 1% of the U.S. land, the ecological impact is much greater affecting15-20% of the landscape (Forman and Alexander 1998). One of the most significant impacts of our road network on wildlife is habitat fragmentation (Forman 2006, Gibbs 1998, Vos 1997, Merriam et al. 1989). Animals move across the landscape to access the various habitat types needed for foraging, breeding, and resting. Roads can destroy established ecological connections, prevent necessary genetic exchange by isolating populations from each other, and for sensitive species increase the risk of extinction (Jaeger et al. 2007). In the White Mountains of New Hampshire, an analysis done for the U.S. Department of Agriculture Forest Service indicated that loss from highway kills was a factor in the extirpation of Canada lynx from the state (Brocke et al. 1993). Road mortality also was an important factor in the failure of an attempted reintroduction of Canada lynx to the Adirondack Mountains of New York in 1991 (Hoving et al. 2005).

Roads also reduce the size of core habitat and increase the amount of edge habitat, resulting in smaller wildlife populations (Raty 1979, Maine Department of Inland Fisheries and Wildlife 2003, Fleischman et al. 1997, Forman et al. 2003). Expanding edge habitat is detrimental to certain wildlife species because increased predation and human disturbance lowers breeding success and reduces habitat use. In addition, changes in microclimate occur far from the edge of the road and degrade habitat (Environmental Law Institute 2003).

Direct impacts of roads on wildlife include habitat avoidance (Forman and Alexander 1998) due to traffic noise interfering with breeding calls and songs (Reijnen et al. 1995, Reijnen et al. 1996), lights, and inhospitable surface; and wildlife-vehicle collisions (Lalo 1987, Ashley and Robinson 1996, Gonzalez-Prieto 1993 *In* Seiler 2003). Indirect impacts include changes in land use due to increased human access, chemical contamination from vehicle exhaust and road treatments (Trombulak and Frissell 2000, Buech and Gerdes U.S. Forest Service, Forestry Sciences lab, Grand

Rapids, Minn., unpubl. data *In* deMaynadier and Hunter 2000); and the spread of invasive plant species (Forman and Alexander 1998). Both the direct and indirect impacts of roads threaten wildlife populations and their persistence on the landscape.

The conflict between our need for safe and efficient roads and conservation of wildlife and wildlife habitat points out the need for tools that measure the potential risks to wildlife associated with roads and the development that goes with them. Roads through wetland areas are known to have impacts to water quality and wildlife. We have developed a tool to help planners and regulators determine where new roads should or should not be located or relocated, and determine which roads should or should not be upgraded for higher traffic levels.

Discussion

Measuring Road Impacts on Wildlife

We used the current available literature to assess what factor(s) would be most appropriate to use in developing a tool to predict impacts of roads on wildlife and wildlife habitat. Studies were taken predominately from Europe and North America and included a variety of habitat types. Although the science of road ecology is still emerging, we found original source data to evaluate impacts of road location, road surface (paved vs. unpaved), road width, road speed, and traffic volume on wildlife.

Road width and speed have an impact on wildlife but have not been found to be as significant as traffic volume (Jaeger et al. 2005). In general, narrower roads and roads with lower traffic speed have fewer impacts than wider roads or roads with higher traffic speed (Forman et al. 2003, Jaeger et al. 2005). Oxley et al. (1974) found road surface was not a critical inhibiting factor for mammals.

Road location was repeatedly found to be important in determining impacts of roads on wildlife (Compton 1999, Gonzales-Pretio et al. 1993 *In* Seiler 2003). The highest collision rates occur in undisturbed areas where development is not significant (Gonzales-Pretio et al. 1993 *In* Seiler 2003). Impacts from roads adjacent to or near wetlands are especially pronounced (Ashley and Robinson 1996, Glista et al. 2008). The number of species of plants, reptiles, amphibians, birds, and mammals declined between 12-19% as the density of roads increased near wetlands and the effects can extend between 1600 and 6500 feet (approx. 488 – 1,980 m) (Findlay and Houlahan 1997). In Maine, riparian habitats are used by 85% of the vertebrate species (Krohn and Hepinstall 2000) and are considered the skeleton or backbone of the landscape that, if protected will ensure that approximately 50% of Maine's wildlife will continue to persist (Krohn and Hepinstall 2000). Species often live, nest or den in the riparian habitat while others take advantage of the rich life in these areas for feeding or use them as travel corridors.

Traffic volume is especially important when evaluating road impacts to wildlife. Jaeger et al. (2005) conducted a quantitative analysis of impacts of various road characteristics on population persistence. Although vulnerability varies among species, he found that traffic volume had the greatest effect on population persistence (Jaeger et al. 2005) and was also an indicator of habitat fragmentation (Jaeger et al. 2007). Based on a review of 30 different papers that studied traffic volume impacts to various wildlife species (Table I) and Jaeger's work, we conclude that traffic volume is a key factor in determining impacts to wildlife.

Traffic Volume	Traffic Count Collection Method	Species	Level of Impact[1]	Location	Reference
120	AADT estimated by authors[2]	Southern Leopard Frog	Onset	Florida. USA	Palis 1994.
>100	Vehicles/lane/day[3]	Land turtles (includes Box, Spotted, Blanding's, Wood, Gopher Tortoise)	Substantial	Eastern & central regions, USA	Gibbs and Shriver 2002.
>200	Vehicles/lane/day[4]	Snapping Turtle	Substantial	Eastern & central regions, USA	Gibbs and Shriver 2002.

[1] Level of Impact increases from Onset →Substantial→Major Habitat Avoidance→Near Complete Barrier
[2] Calculated by Charry/Jones from study reporting 12 families on dead end road using estimate of 10 trips/single family home from ITE Trip Generation Manual (Institute of Transportation Engineers 2003)
[3] Density dependent (based on areas with > 1 km of roads/kmsq)
[4] Density dependent (based on areas with >2 km of roads/kmsq)

Traffic Volume	Traffic Count Collection Method	Species	Level of Impact[1]	Location	Reference
>250	Vehicles/lane/day [5]	Spotted salamander	Substantial	Massachusetts, USA	Gibbs and Shriver 2005.
300	Vehicles/day provided by landowner on private road	Salamanders	Onset	Maine, USA	deMaynadier and Hunter 2000.
300-500	Vehicles/day winter[6] only	Carnivores (includes coyote, wolf, cougar, lynx, marten, wolverine)	Onset	Central Canadian Rocky Mountains	Alexander et al. 2005.
300-2200	AADT	Snakes (primarily, gopher snakes, western rattlesnakes)	Substantial	Southeastern Idaho, USA	Jochimsen 2005.
336	Vehicles/day collected by traffic counter during study	Common Toad (Bufo bufo)	Onset	The Netherlands	van Gelder 1973.
500-3500	AADT	Frogs and Toads	Onset	Ottawa, Canada	Fahrig et al. 1995.
500-5000	Vehicles/day winter[7] only	Ungulates (includes elk, moose, sheep, deer)	Onset	Central Canadian Rocky Mountains	Alexander et al. 2005.
576-960	AADT estimated by authors[8]	Common toad (Bufo bufo)	Substantial	Germany	Kuhn 1987 *In* Reh and Seitz 1990.
624	Calculated from 26 cars per hour	Common Toad	Substantial	Germany	Heine 1987 *In* Reh and Seitz 1990.
700-3000	per 24 hour (methods unknown)	Birds, 4 species Tetraonid (grouse)	Onset	Finland Forest	Raty 1979.
835	AADT personal communication from author[9]	Amphibians	Substantial	New Brunswick, Canada	Mazerolle 2004.
1000	AADT Noise rises over 50 dB(A) at this traffic volume	Birds	Onset	The Netherlands	Forman 2003 based on studies by Reijnen 1995, 1996, 1997.
1068-3231	Summer AADT	Mammals, birds, amphibians	Onset/Substantial	Alberta, Canada	Clevenger et al. 2003.
1440	1 car/minute (extrapolated to 24 hour day)	Toad (Bufo bufo)	Substantial	The Netherlands	van Gelder 1973.
1900-6287	AADT	Primarily amphibians, reptiles, also birds, mammals (carnivores included coyote, mink, masked shrew, red fox)	Substantial	Indiana, USA	Glista et al. 2008.
2000-4000	AADT	Moose	Substantial	South-central Sweden	Seiler 2005.
2400	AADT estimated by authors[10]	Elk	Substantial	Arizona, USA	Gagnon et al. 2007.
3050	Average summer daily from Ontario Ministry of Transportation	Amphibians (Northern Leopard frog most common,) reptiles (Garter snake and painted turtle most common), birds (Red-winged blackbird most common), mammals (carnivores included short-tailed shrew, little brown bat, red bat, long-tailed and short-tailed weasel, mink)	Substantial	Ontario, Canada	Ashley and Robinson 1996.
3200	24 hour counts (April 1 – July) by Danish Road Directorate	Amphibians	Substantial	Northern Denmark	Hels and Buchwald 2001.

[5] Density dependent (based on areas with >2.5 km of roads/kmsq)
[6] AADT for these roads were reported as 3000 and 5000 but did not assess impacts to wildlife during peak/summer seasons.
[7] AADT for these roads were reported as 5000 and 14,000 but did not assess impacts to wildlife during peak/summer seasons.
[8] Calculated by Charry/Jones from study reporting 24-40 cars per hour
[9] Night traffic volume collected by traffic counter 13.6 vehicles/hour, range 5-26 vehicles/hour at night
[10] Calculated by Charry/Jones from permanent traffic counter recording mean traffic volumes of 100 vehicles/hour.

Traffic Volume	Traffic Count Collection Method	Species	Level of Impact[1]	Location	Reference
4000-6000	AADT	Moose	Substantial	South-central Sweden	Seiler 2005.
4560	Cars per average weekday	Grassland birds (lapwing & godwit)	Substantial	The Netherlands	van der Zande et al. 1980.
4700	AADT	Wolf	Substantial	Wisconsin, USA	Unger 1999 *In* Kohn et al. 2000.
5000	AADT Steep increase in noise level at this traffic volume	Birds	Substantial	The Netherlands	Forman 2003 based on studies by Reijnen 1995, 1996, 1997.
5000	Cars per day	Grassland birds	Substantial	The Netherlands	Reijnen et al. 1996.
5000-6000	AADT	Frogs and Toads	Substantial	Ottawa, Canada	Fahrig et al.1995.
6000 +/-	AADT estimated by authors[11]	Turtles including, fully or semiterrestrial, small-bodied and large-bodied pond turtles	Near Complete Barrier	USA	Gibbs and Shriver 2002.
7000 - 20,000	Number of vehicles entering the park in July and February respectively, underestimate	Snakes (Ribbon snake, Garter snake, Florida water snake, Cottonmouth)	Near Complete Barrier	Florida, USA	Bernardino and Dalrymple 1992.
7311	Vehicles per average weekday	Grassland birds (lapwing & godwit)	Substantial	The Netherlands	van der Zande et al. 1980.
8000-15,000	AADT	Grassland birds	Substantial	Massachusetts, USA	Forman et al. 2002.
8200	AADT calculated by authors[12]	Turtles	Near Complete Barrier	Florida, USA	Aresco 2005.
8500-13,000	AADT	Frogs and Toads	Substantial/Near Complete Barrier	Ottawa, Canada	Fahrig et al. 1995.
10,000	Vehicles/day	Terrestrial vertebrates	Near Complete Barrier	Europe	Seiler 2003. Many references cited.
10,000	AADT Nearly 70 dBA at this traffic level, then gradual increase in dBA as traffic volume increases level	Birds	Major Habitat Avoidance	The Netherlands	Forman 2003 based on studies by Reijnen 1995, 1996, 1997.
10,000	Vehicles/day	Woodland birds	Major Habitat Avoidance	The Netherlands	Reijnen et al. 1995.
10,000	Vehicles/day	Birds, woodland & grassland	Major Habitat Avoidance	The Netherlands	Reijnen et al. 1997.
10,000-100,000	Vehicles/day	Migrating salamander	Near Complete Barrier	Massachusetts, USA	Gibbs and Shriver 2005.
11,000	AADT	Small mammals	Near Complete Barrier	Ontario, Canada	McGregor 2003.
14,000	AADT	Mammals, birds, amphibians	Near Complete Barrier	Alberta, Canada	Clevenger et al. 2003.
14,400	AADT estimated by authors[13]	Elk	Major Habitat Avoidance/ Near Complete Barrier	Arizona, USA	Gagnon et al. 2007.
15,000	Vehicles/day used in model to represent busy highway	Amphibians	Near Complete Barrier	Northern Denmark	Hels and Buchwald 2001.

[11] Calculated by Charry/Jones based on assumption that “several thousand vehicles/lane/day” equals 6000+/-
[12] Calculated by Charry/Jones based on 162% increase AADT occurring from 1977 to 2001.
[13] Calculated by Charry/Jones based on permanent traffic counter recording mean traffic volumes of 600 vehicles/hour.

Traffic Volume	Traffic Count Collection Method	Species	Level of Impact[1]	Location	Reference
15,000-30,000	AADT	Grassland birds	Major Habitat Avoidance	Massachusetts, USA	Forman et al. 2002.
21,500	AADT	Turtles	Near Complete Barrier	Florida, USA	Aresco 2005.
>=30,000	AADT	Grassland birds	Major Habitat Avoidance	Massachusetts, USA	Forman et al. 2002.
50,000	Cars per day	Grassland birds	Major Habitat Avoidance	The Netherlands	Reijnen et al. 1996.
50,000	Vehicles/day	Birds, woodland & grassland	Major Habitat Avoidance	The Netherlands	Reijnen et al. 1997.
54,000	Cars per average weekday	Grassland birds (lapwing & godwit)	Major Habitat Avoidance	The Netherlands	van der Zande et al.1980.
60,000	Cars per day	Woodland birds	Major Habitat Avoidance	The Netherlands	Reijnen et al. 1995.

Table I: Levels of Impact to Wildlife from Various Traffic Volumes (Ranked Low to High) on Species or Groups of Species.

Traffic Volume as a Tool for Measuring Road Impacts to Wildlife

Traffic volume is regularly measured by state transportation departments to assess the need for road improvements and is therefore often readily available. Traffic engineers use Average Annual Daily Traffic (AADT) to measure traffic volume. True AADT volume is measured at permanent stations and counts every car, every day, and calculates the average for the year. AADT volumes can also be estimated by sampling (e.g. counting during certain times) and then adjusting the count using various factors (seasonality of use, type of use - urban vs. rural etc.). Finally, traffic volume can also be estimated into the future, albeit with less certainty, using various assumptions and data collected on similar types of roads from across the United States and reported in the ITE *Trip Generation Manual* (Institute of Transportation Engineers 2003).

Although AADT is the most easily collected and comparable measure of traffic volume, it is not available for all roads. Therefore, many studies that measured impacts of traffic on wildlife populations collected their own information on traffic volume using traffic counters during their studies (Mazerolle 2004, van Gelder 1973) while others simply did not identify whether or not the measure was AADT (Raty 1979, Reijnen et al. 1995, Reijnen et al. 1997, deMaynadier and Hunter 2000). While traffic counts are not true AADT, it is a useful measure of traffic volume observed during the study period and was included as part of our analysis to determine impacts to wildlife and wildlife habitat. It is important to note that traffic volume can vary greatly by season and time of day, as can wildlife movements. Our analysis used all types of traffic measures in order to include the most information on impacts.

We identified different levels of impacts to wildlife based on traffic volume (Table I). The risk of impacts was assessed for various groups of wildlife species, including amphibians, reptiles, birds, and mammals. Each level of risk included an assessment of when impacts to different species groups would likely begin and when it was likely to become a serious threat.

Amphibians

Many amphibians, such as the spotted salamander and wood frog, travel regularly between wetlands, where they breed, and uplands, where they live during the non-breeding season. This movement pattern makes them vulnerable to road mortality and habitat fragmentation. Amphibians are particularly vulnerable to road mortality at relatively low traffic volumes (van Gelder 1973, Kuhn 1987 *In* Reh and Seitz 1990, Heine 1987 *In* Reh and Seitz 1990), are killed in large numbers on roads going through or adjacent to wetlands (Ashley and Robinson 1996, Glista et al. 2008), have been documented to avoid crossing roads (deMaynadier and Hunter 2000), and are highly sensitive to chemical contamination (Buech and Gerdes, U.S. Forest Service, Forestry Sciences Lab, Grand Rapids, Minn., unpubl. Data *In* deMaynadier and Hunter 2000).

Reptiles

Snakes and turtles are particularly vulnerable to impacts from roads. They have similar life histories, including terrestrial travel between breeding and nonbreeding habitats, and relatively long life with slow reproduction rates. In one study, 73% of the snakes observed on the road were found dead or injured at traffic volumes of 7,000 to 20,000 (Bernardino and Dalrymple 1992). According to Gibbs and Shriver (2002, p. 1649), it is likely that "as little as 2-3% additive annual mortality is more than most turtle species can absorb and still maintain positive population growth rates". Compton (1999) found that, for Maine wood turtle populations, loss of only two adults from a population can devastate that population and are they are especially vulnerable to being killed by vehicles (Klemens 1989 *In* Compton 1999). Gibbs and Shriver (2002) concluded that land-use planners should perhaps consider near roadlessness as a criterion for habitat suitability for land turtles. "This perhaps places land turtles and, in some situations, large-bodied pond turtles in the company of grizzly bears and gray wolves as fauna for which road networks may be a key limiting factor to population recovery efforts" (Gibbs and Shriver 2002, p. 1651).

Birds

Mortality from bird-vehicle collisions is a significant issue. It is estimated that 80 million birds are killed annually in the United States (Erickson et al. 2001). For example, Glista et al. (2008) found 34 dead chimney swifts along a road bisecting a bog which were probably the result of low-flying birds striking vehicles while pursuing insects. Many bird species have been documented to avoid habitat adjacent to roadways at increasing levels as traffic intensity increases. At traffic volumes of 1000 AADT, breeding populations of woodland birds begin to decline, and at traffic volumes of 10,000 AADT, breeding populations of birds in coniferous habitat were reduced as far as 30-1500 m from the road. (Reijnen et al. 1997).

Mammals

Wide-ranging mammals such Canada lynx, gray wolves, moose, bear, bobcat, fisher, and American marten have large home ranges in which to find food, breed, and raise their young. They often must cross and re-cross roads to access all parts of their home range and to disperse to new territories, making them vulnerable to collisions with vehicles (Ashley and Robinson 1996, Glista et al. 2008). For example, a study from 1970-2005 in Wisconsin showed a high percentage of wolf mortality was associated with human causes (70.6%), with vehicle collisions higher than any other cause (31.2%) (Wisconsin Dept. of Nat. Resources 2007). Moose-vehicle collisions peak at traffic volumes between 4000-6000 vehicles per day (Seiler 2003). Due to habitat fragmentation and mortality to carnivores, wildlife crossing structures are recommended at traffic volumes of 2000-3000 AADT (Ruediger et al. 1999). Many species of both carnivores and ungulates have also been found to avoid crossing roads (Alexander et al. 2005) or locate breeding activities away from major highways (Unger 1999 *In* Kohn et al. 2000). Fisher were found to use roads as the perimeter of their home ranges (Arthur et al. 1989). As traffic volume increases, habitat adjacent to roads is avoided by elk (Gagnon et al. 2007).

Determining Impact Thresholds

We reviewed the studies summarized in Table I to identify the severity of impacts to wildlife at different traffic volumes. Although impacts from increasing traffic volumes actually occur along a continuum (Figure 1), we identified thresholds to provide clear guidance to land use and transportation planners.

Studies were organized by increasing traffic volume (Table I) and then assessed for severity of impacts and categorized as one of the following; onset, continuum of substantial impacts, major habitat avoidance, and near complete barrier. Although individual species exhibit unique responses to traffic volume, for the purposes of this paper each species was evaluated as a part of a species group (amphibians, reptiles, carnivores, ungulates, and birds). The severity of the impact was used to determine natural breaks in traffic volume that could function as thresholds. These breaks are summarized in Table II. Impacts we assessed included road mortality, wildlife-vehicle collisions, extent of population reduction, barrier effects, and adjacent habitat avoidance.

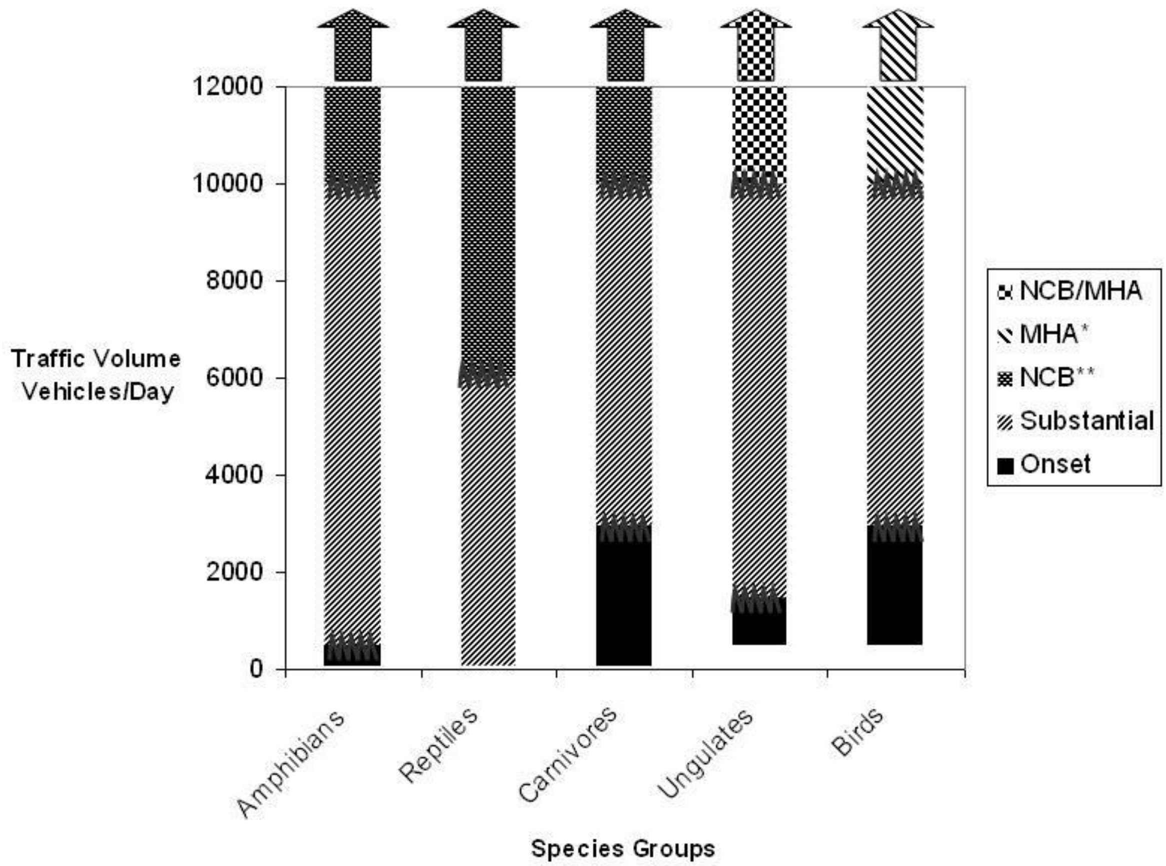

Figure 1: Continuum of Impact to Species. Impacts for five different species groups (Amphibians, Reptiles, Carnivores, Ungulates and Birds) are shown for different traffic volumes (vehicles/day). Impacts for each species group occurred across a continuum but include thresholds for five different levels of severity; Onset, Substantial to Severe impacts, Major Habitat Avoidance (MHA) and Near Complete Barrier (NCB). [^^^] thresholds are provided for guidance and occur over a range of traffic volumes.

Vehicles/Day	Onset of Impacts	Continuum of Substantial Impacts	Major Habitat Avoidance	Near Complete Barrier
100-500	Amphibians Carnivores	Amphibians[14] Reptiles		
500-1500	Ungulates Birds	Amphibians (increases for reptiles)		
1500-3000		Ungulates (increases for amphibians & reptiles)		
3000-6000		Carnivores Birds (increases for amphibians, reptiles, ungulates)		
6000-10,000		Increases for amphibians, carnivores, ungulates, birds		Reptiles
10,000+			Birds Ungulates	Amphibians, Reptiles, Carnivores, Ungulates Small mammals

Table II: Traffic Volume Impacts on Wildlife at Different Thresholds

[14] Road density dependent

Onset of Impacts

Onset of adverse impacts for amphibians began at traffic volumes of 100 AADT. In this traffic volume range, mortality of up to 50% of amphibians was observed on the road (Palis 1994, van Gelder 1973), or was a significant barrier to amphibians (deMaynadier and Hunter 2000). Onset for carnivores and ungulates was defined as detectible reduction in habitat permeability (change in rates of animal movement) and began at traffic volumes of 100-500 AADT (Alexander et al. 2005). Alexander et al. (2005) used winter tracking studies and found that roads began to present a barrier effect for carnivores (coyote, wolf, cougar, lynx, marten, and wolverine) and ungulates (elk, moose, sheep, deer). As groups, these species were less likely to cross and more likely to make multiple approaches to roads in an attempt to cross at winter traffic volumes (Alexander et al. 2005). Woodland birds were documented as starting to avoid habitat (i.e. reduced densities) at 42 dB(A) (Reijnen et al. 1995). We determined the onset of impacts for woodland birds at traffic levels of 1000 vehicles/day because Forman et al. (2003) reported that noise levels over 50 dB(A) occur at this traffic volume. Impacts to grassland birds occurred at lower traffic volumes than with woodland birds. Avoidance is caused by traffic noise which is louder as traffic increases and travels farther through grasslands than woodlands.

Continuum of Substantial Impacts

Impacts within this category generally increased along a continuum from substantial to more severe with increasing levels of traffic volume. We looked for a change in severity of impacts within a species group to determine the beginning of a new threshold of impact (Table II).

Impacts to reptiles were determined significant when annual adult mortality rates resulted in a population decline for turtles (Gibbs and Shriver 2002). For snakes, Jochimsen (2005) compared 15 studies that counted snakes found dead-on-road (DOR) and then determined snake mortality within his study area as "intermediate" which we considered a significant impact.

Significance was identified for amphibians in studies observing successful versus unsuccessful road crossings with >= 50% mortality (Kuhn 1987 *In* Reh & Seitz 1990, Heine 1987 *In* Reh & Seitz 1990, Mazerolle 2004), studies documenting >= 6.7 individuals DOR/km/day (Glista et al. 2008, Ashley and Robinson 1996), or population studies documenting >=25% road mortality of moving breeding adults (Gibbs and Shriver 2005, van Gelder 1973, Hels and Buchwald 2001). Migrating spotted salamanders were unable to sustain road mortality levels of 20-30% of moving adults, leading to local population extirpation within 25 years (Gibbs and Shriver 2005).

Increased impacts as traffic volume increases as a continuum for amphibians was demonstrated in several studies. Fahrig et al. (1995) compared traffic volume ranges of 500-3500 to 5000-6000 to 8500-13,000 AADT and measured populations of frogs and toads and found significant negative impacts on local density and mortality based on three factors; 1) the number of dead and live found per km decreased as the AADT increased; 2) the proportion of dead increased as the AADT increased; and 3) the density decreased with increasing AADT. Mazorelle (2004) found that American toads were found DOR in larger number with increasing traffic during night driving surveys. These increases are apparent in road mortality studies that documented road mortality on roads adjacent and through riparian habitat. Road cruising surveys documenting all species encountered (>60 species), found that 95% DOR were amphibians and reptiles (Glista et al. 2008). At traffic volume of 1900 AADT, 4.6 herptiles were found DOR per km per day and at traffic volume of 6287 AADT 36 herptiles were found DOR per km per day. A similar study through a wetland in Ontario using walking and bicycling surveys, documented 100 species DOR of which 92.1% were amphibians and averaged 11.65 amphibians DOR per km per day at 3050 AADT (Ashley and Robinson 1996).

Ungulate impacts were considered significant when collisions were greater than10 moose-vehicle collisions per 100 km at 2000 AADT (Seiler 2005) or when the average probability of elk occurrence within 200 m of the road was approximately 40% (Gagnon et al. 2007). This probability of habitat use decreased as traffic volume increased. Highest frequencies of collisions were 16.7 moose-vehicle collisions per 100 km at traffic volumes of 4000-6000 AADT (Seiler 2005).

Road mortality of carnivores was particularly high between 3000-6000 AADT in habitats adjacent and through wetlands. Glista et al. (2008) and Ashley and Robinson (1996) both documented carnivore mortality, including coyote, mink, shrew, weasel, fox and bats, on roads adjacent to wetland habitats on roads ranging from 1900-6287 AADT. Clevenger et al. (2003) documented a higher vulnerability to road mortality for mammals, including coyote, American marten, and mink, on a road with traffic volumes of 1068-3231 summer AADT than a major highway with traffic volumes of 14,000 AADT. In addition, wolves located their dens in the center of their territories away from roads with traffic volumes of 4700 AADT (Unger 1999 *In* Kohn et al. 2000).

For grassland birds, a steep increase in road noise occurs at about 5000 vehicles per day (Forman et al. 2003) resulting in a reduction in breeding density and reduction of populations in habitat adjacent to roads within 20-1700 m (Reijnen et al. 1996, van der Zande et al. 1980). Population loss was estimated to be 12-56% within 100 m of roads for most species studied, and beyond 100 m population loss was estimated to be > 10% (Reijnen et al. 1996). Black-tailed godwit population declined 22% from 0-500 m and oystercatcher declined 44% from 0-500 m and 36% from 0-1500 m. Although one study (Forman et al. 2002), did not find a significant impact on the distribution of grassland birds at traffic levels of 3000-5000, densities and population declines have been documented elsewhere (Reijnen et al. 1996). Road mortality for birds was also documented on a continuum on roads with lower traffic volume (1068-3331 summer AADT) to higher traffic volume (14,000 AADT), with roadside foragers most frequently killed (Clevenger et al. 2003).

Major Habitat Avoidance

Birds and ungulates respond to increased traffic volume through major habitat avoidance (MHA), which is a decrease of habitat use and/or reduced population densities in habitats adjacent to roads (Table I). As the traffic volume increases, bird population density continues to decline farther from the road (Forman et al. 2003) and the probability of habitat use by ungulates declines (Gagnon et al. 2007). We used this impact to define MHA for these two species groups (Table II).

In grassland birds, noise is also an important factor but visual stimuli cannot be excluded for certain (Reijnen et al. 1997). Forman (2003) reported noise levels increase to nearly 70 dB(A) at traffic volumes of 10,000 AADT. At this traffic volume, grassland bird species had population reductions at a distance of up to 2180 m from roads (365 m when probable unrealistic values are excluded) (Reijnen et al. 1997). At traffic volumes of 50,000 vehicles/day there were increasing impact distances to a maximum of 3530 m (930 when probable unrealistic values are excluded) from roads (Reijnen et al. 1997) and an estimated population decrease of 12-52% within 500 m from the road and five species had population reductions of 14-44% up to 1500 m from the road (Reijnen et al. 1996). These findings are supported in other studies (Forman et al. 2002, van der Zande et al. 1980).

In woodland habitats, noise is the most critical factor causing reduced densities of birds along roads (Reijnen et al. 1995). Sixty percent of the woodland species studied had reduced densities of 20-98% within 250 m of road (Reijnen et al. 1995). MHA for woodland birds was defined as occurring at traffic volumes of 10,000 AADT when researchers observed a reduction in breeding bird densities at distances of 40-1500 m from the road (305 m when probable unrealistic values are excluded) (Reijnen et al. 1997). Impacts continued to increase with increasing traffic volume and at 50,000 AADT MHA occurred up to 2800 m from road (810 m when probable unrealistic values are excluded) (Reijnen et al. 1997).

MHA for ungulates occurred when the mean probability of habitat use within 200 m of road declined to <20% (Gagnon et al. 2007).

Near Complete Barrier

For most species, roads with traffic intensity over 10,000 vehicles per day become a near complete barrier (NCB) for movement. Though an individual animal may be able to safely cross a high volume highway one or more times, the odds of a successful crossing are slim. Time of day, time of year, the speed and behavior of the animal, and its ability to make intelligent crossing decisions all influence the outcome. However, one safe crossing does little to counter the cumulative multiple negative impacts to local and regional populations that occur on and adjacent to the road, in some cases hundreds or thousands of meters.

Seiler (2003, p. 29) identified roads with traffic volumes of 10,000 AADT as an "insurmountable barrier" and cites several sources. Gibbs and Shriver's (2005, p. 288) model found these roads to be "wholly lethal" to migrating salamanders. Hels and Buchwald (2001) calculated a 0.89-0.98 probability of mortality when amphibians attempt to cross a 15,000 AADT road and essentially a complete barrier (probability of mortality reaching 1.0) at traffic volumes above this level. For terrestrial and semi-terrestrial, small and large-bodied pond turtles, modeling work identifies roads with traffic volumes of 10,000 AADT or more as essentially impenetrable (Gibbs and Shriver 2002). Using Gibbs and Shriver's model (2002) modified from Hels and Buchwald (2001), Aresco (2005) estimated approximately 68% probability of mortality for turtles on a road with a traffic volume of 8200 AADT. Traffic increased to 21,500 AADT (a 162% increase) from 1977 to 2001 resulting in a probability of 98% mortality of turtles. The results were verified by field surveys in the same location documenting 100% mortality (Aresco 2005). Clevenger et al. (2003) concluded that lower bird and mammal road-kills on the road with traffic volume of 14,000 AADT was probably due to avoidance of the highway. No relocated small mammals returned across a road with traffic volume over 11,000 AADT whereas some successfully returned on roads with as much as 7000 AADT (McGregor et al. 2003).

Recommendations for Use of the Traffic Volume Tool in Land Use Planning

Traffic volume and road location were the two most important factors in determining impacts to wildlife. Traffic volume can be readily measured and used to determine how various patterns of development will impact wildlife and wildlife habitat. Although we have identified thresholds of impacts, it is important to note that impacts increase over a continuum and thresholds may need to be adjusted to avoid impacts to wetland-dependant species or endangered species.

It is also important to recognize impacts occur beyond the immediate access roads of a proposed development or beyond road segments scheduled for upgrades. Ruediger et al. (1999) recommended that highway agencies should increase the planning scale to at least the entire highway length in the northern Rocky Mountains and in other areas where carnivores are a concern. Traffic impacts will occur miles beyond a proposed development and should be taken into consideration. For example, assessment of impacts from resorts and lodging development within remote areas should include roads used for travel to and from airports, major highways, and recreation destinations that are likely to be visited by potential customers of the resort.

We offer the following concepts and recommendations to assist land use planners, conservationists, and developers in minimizing road impacts to wildlife and maximizing conservation benefits.

Land Use Planning Concepts for Avoiding Impacts of Traffic on Wildlife:

1. Avoid road building in large undeveloped habitat blocks and remote areas (*consider road closures*)
2. Avoid increased traffic volumes on roads in rural and remote areas (*prevent development that requires access through large undeveloped habitat blocks and remote areas*)
3. Concentrate traffic on existing highly traveled roads
4. Avoid locating new roads near wetlands, ponds, lakes, rivers, and streams

Recommendations for Implementing Traffic Volume Tool into Land Use Planning:

1. Concentrate new traffic on existing high volume roads (particularly roads approaching 10,000 vehicles/day)
2. Avoid increasing traffic to 3000-6000+ vehicles/day range
3. Limit new traffic on low use roads (e.g. 500-1500 vehicles/day) in rural and remote areas to less than 2000-2500 vehicles/day
4. Limit new traffic on remote/logging roads to less than 300-400 vehicles/day
5. On existing roads that bisect or occur near wetlands, ponds, lakes, rivers and streams, avoid increasing traffic volume above its current threshold range
6. On existing roads, use wildlife-crossing structures to facilitate animal movement. (*NOT a solution to allow poorly located roads*)

These concepts and recommendations incorporate road location and traffic volume in order to minimize the impacts to wildlife and to help avoid fragmenting habitats of species vulnerable to increased traffic.

Conclusions

Most species are impacted by traffic volume, however different impacts are present at various traffic volumes. Traffic volume can be used as a tool to assess overall risk to wildlife and wildlife populations in order to help planners and regulators make informed decisions on how to better conserve species across the landscape. Traffic volume has the clear advantage in that it is readily measured and can be realistically used to compare roads and predict changes and determine baseline volumes. In addition, this measure is often readily available from state transportation agencies at least on many roads, is a tool regularly used by traffic engineers, and is broadly used by the scientific community to estimate impacts to wildlife. We recommend that researchers, in future studies, include AADT or estimates of AADT in addition to seasonal counts or counts taken during a study. AADT estimates will allow studies to be easily compared and can assist in further refining the thresholds determined in this paper.

Biographical Sketches

Barbara Charry is a Wildlife Biologist and GIS Manager at Maine Audubon with 20 years experience in endangered species management, natural history information, and information management. She holds a B.A. from Grinnell College and an M.S. from Antioch New England Graduate School. She has worked as an interpretive naturalist, wildlife rehabilitator, field biologist, and grassroots activist coordinator. Over the last 10 years, the focus her work has been the impacts of sprawling development on Maine's wildlife. Much of her work on road ecology has involved researching and synthesizing scientific information and sharing it with local, regional and state decision-makers. She became a state leader in this work in 2001 when Maine Audubon became a founding partner of Maine's nationally acclaimed Beginning with Habitat program, an innovative public/private partnership that provides practical tools for Maine communities to incorporate wildlife and habitat conservation into local land use planning. Under Barbara's leadership, Maine Audubon convened the first-ever state-wide conference on road ecology in Maine. She has also presented at the International Conference on Ecology and Transportation. She presented expert testimony on road impacts at public hearings on Plum Creek's massive development proposed for Maine's Moosehead Lake region. She has written several guides for land use decision makers and community members on the impacts of development on wildlife including a community conservation guide, "Conserving Wildlife On and Around Maine Roads".

Jody Jones is a wildlife ecologist with experience in policy issues regarding endangered and threatened species, migratory birds and bats, ecology of coastal beaches, wetland and riparian habitats and toxics in the environment. She also directs the recovery of endangered Piping Plovers and Least Terns in Maine. Jody holds a B.S. in natural resources and a M.S. in wildlife ecology and management from the University of Michigan, where she conducted research on the wintering ecology of waterfowl. She has taught courses in ornithology, mammalogy and the coastal ecology of Maine. In her tenure at Maine Audubon, Jody has provided expert testimony before the Board of Environmental Protection, Land Use Regulation Commission, U.S. Fish and Wildlife Service and the Maine legislature on a variety of issues including impacts of wind power on wildlife, risks associated with coyote snaring to rare species, dune and beach habitat protection and the recovery of Atlantic salmon, Canada lynx and wolves.

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