Predictive Models of Herpetofauna Road Mortality Hotspots in Extensive Road Networks: Three Approaches and a General Procedure for Creating Hotspot Models that are Useful for Environmental Managers

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Abstract

Road-kill and connectivity blockages caused by roads and road traffic can result in serious population declines of amphibians and reptiles. Landscape-scale modeling of road mortality risk and road-caused habitat fragmentation indicate that effective monitoring and mitigation of these impacts on herpetofauna require attention to the entire regional road network. The time and expense to adequately survey an extensive road network may be prohibitive to agencies, however, so there is a need for accurate and efficient models to prospectively identify the most promising sites for monitoring and mitigation. In this paper, I review three general methods by which road-kill hotspots and connectivity blockages caused by roads can be predicted throughout a road network by creation and use of predictive models. I also review two studies, one focused on all herpetofauna and a second focused on freshwater turtles, which were designed to identify valid predictors of hotspots of road mortality in northeastern New York State, USA. In this paper, I propose a procedure to develop survey methodologies and to create and validate predictive hotspot models that use publically-available GIS data to locate severe road-kill sites or connectivity blockages for reptiles and amphibians. I also explain some of the informational and logistical challenges to developing hotspot models that are useful for management agencies. I argue that predictive hotspot models are tools that are essential for effective and economical whole road-network survey and mitigation, and for planning new road routes that avoid areas of high road-kill risk or critical corridors for habitat and population connectivity. While such models have already proven useful for mammals, hotspot models may be especially effective for reptiles and amphibians, which typically have hotspots that are short in length but severe in effect.

Introduction

Mitigation projects aimed at reducing road mortality or maintaining habitat connectivity for reptiles and amphibians are typically implemented at a small number of high-profile sites in response to pressure of local interest groups or regulatory agencies; it is likely that most sites for effective mitigation are missed by this ad hoc approach (Spellerberg 2002, Evink 2002). Reptile and amphibian populations often have the characteristics of either a metapopulation, or a single population in which individuals move among multiple, spatially separated patches (e.g. hibernacula, breeding sites, and foraging habitat); in either case movement between patches often necessitates crossing roads (Marsh and Trenham 2000, Semlitsch 2000, Roe and Georges 2007). Unless mitigation technologies and best-practices for reducing herpetofauna road mortality and maintaining connectivity are implemented systemically throughout a road network, some species are likely to decline in densely-roaded landscapes (Gibbs and Shriver 2002, 2005, Roe et al. 2006, Compton et al. 2007, Litvaitis & Tash 2008). Population declines may be a consequence of excessive road mortality when animals attempt to cross roads, or due to reduced habitat connectivity that results when animals avoid crossing them.

Mitigation technologies such as culverts, fencing, and signage have been used to reduce road mortality and maintain habitat connectivity for reptiles and amphibians. However, these technologies are expensive or labor-intensive, making them impractical to implement throughout a road network (see reviews in Evink 2002, Bank et al. 2002, Forman et al 2003, Bissonette & Cramer 2008, Glista et al. 2009). Methods of efficiently and accurately locating critical sites for mitigation are essential for successful systemic environmental management of road-kill and connectivity, since resources (money, time) are severely limited for installation and maintenance of barriers, passageways, and signage; road networks are vast; and reptile and amphibian populations are likely to be subject to severe road mortality or connectivity blockages at multiple sites. Such critical sites include (1) where herpetofauna are most likely to cross roads, (2) where risk of road mortality is highest, and (3) where structural barriers or behavioral avoidance prevent reptiles or amphibians from crossing roads to access resources or other sub-populations.

Note that these three classes of critical sites do not necessarily overlap: critical sites for connectivity may not correspond to the locations where road crossing and road mortality are highest, if critical connectivity sites have features that deter reptiles and amphibians from attempting to cross the roadway or if populations near these sites are already reduced due to past road mortality. Similarly, sites of peak road crossing are not necessarily sites of peak road-kill, since road-kill numbers are a function of both crossing rate and vehicle traffic volume (Seiler & Helldin 2006).

Numerous studies have concluded that reptile and amphibian mortality is often clustered at hotspots, localized segments of road that have disproportionately high densities of road-kill (Langen et al. 2009). If landscape and road features associated with hotspots could be identified, and if data on the spatial dispersion of these predictive features along roads is known, then these predictors could be used to locate critical sites throughout a road-network. Such hotspot modeling is currently being applied to identify critical sites for road crossing by mammals (e.g. Smith 1999, Clevenger et al. 2002, Malo et al. 2004, Ramp et al. 2005, Seiler 2005), and the potential for aiding in systemic management of herpetofauna on roads appears promising. In this paper, I review three ways in which predictive hotspot models can be created 'from the ground up' for predicting critical road segments for reptiles and amphibians, review two case studies from my own research, and provide some recommendations on how road managers might go about generating and validating useful predictive hotspot models for road networks in their regions.

General Requirements for Creating Hotspot Models

To create valid models to predict hotspots of road-mortality or critical linkages for connectivity, seven components are necessary:

(1) Reference locations of representative hotspots.

On a sample of roads that are representative of the road network, one must have empirical data on where road mortality is most dense (or historically most dense before road-kill associated population declines), or where animals would cross if not inhibited by the road and road traffic. This can be done by directly measuring patterns of road-crossing and road-kill, or by tracking movements of animals to document where they cross or are deterred from crossing.

(2) Database of potential correlates.

To use known hotspots on a road network to predict others, it is necessary to have accessible, accurate data on the locations of relevant potential correlates or determinates of critical locations for connectivity or road mortality. Such data could include road segment traffic volumes; locations and density of populations of focal species; land use and land cover around roads; and locations of wetlands, rivers, and other water bodies. Such data must be accurate to an appropriate spatial scale (see next point) to be usable.

(3) Scale.

Hotspots may be the result of highly local conditions such as the habitat in the immediate vicinity of a road segment and the configuration of the road relative to the surrounding landscape (elevated, level or sunken; straight or curved); or else the locations of hotspots may be determined by landscape level patterns of animal abundance, land use, land cover, hydrology, and topography. In model development, it is necessary to determine the best spatial scale(s) at which putative predictors indicate locations of hotspots.

A second issue of scale is how fine a resolution to define hotspots. This is a factor of the spatial extent (length of road) and severity (e.g. density of road-kill above background levels) of individual hotspots, and the degree of spatial clustering of different hotspots in a network. Ideally, hotspots will be short in length and very severe. Short, severe hotspots can be more easily mitigated by barriers and passageways or other mitigation methods than when road-kill or critical connectivity blockages are distributed over a broader extent of the road.

(4) Model generation.

Hotspot models are typically generated using some form of exploratory stepwise general linear modeling. One typical method is to compare a set of locations that are known hotspots to a set of random locations on the road network. Logistic regression is used, with the dependent (outcome) variable dichotomized as hotspot vs. random location. Backwards (starting with a saturated model of all potential predictors) and forwards (starting with the single best predictor) stepwise procedures can be used, or any other procedure that facilitates exploration of the most promising candidate models. Note that the goal is to identify models that can be used easily by managers to locate hotspots, so simplicity should be a consideration when selecting models to explore. Also note that if the correct spatial scale for including land use (or other predictors) is unknown, multiple models with the same variable set measured at different spatial scales (e.g. land use at 100 m, 500 m, and 1000 m around a location) might be necessary.

(5) Method of model selection.

The method of model selection should provide a clear procedure for evaluating alternative models. Models should be evaluated by both (1) comparing the relative fit of alternative models, and (2) comparing the accuracy of the best model at predicting hotspots. For comparing models and identifying a set of best models, I advocate using methods described in Burnham and Anderson (1998), which uses Akaike's Information Criterion (AIC). The procedures described in Burnham and Anderson's (1998) book indicate how models can be compared, and also provide a way to compare the relative importance of different predictors that are used in the set of evaluated models. To evaluate the accuracy of best models at predicting hotspots vs. other locations (accurate models having both few misses and few false positives), there are several valid methods reviewed in Fielding and Bell (1997). When evaluating models, the 'best' model for the purpose of locating hotspots should be similar in terms of the quantitative criterion (AIC) to the one that is the best by this metric, be accurate at prediction (few misses or false positives), use predictive variables for which accurate data exist along all roads within the network of concern, and be easy to use and interpret by road managers.

(6) Method of model validation.

In principal, during the model development and selection stage, only half of the data could be used to generate the model, and the other half used to validate. This may be unwise if the amount of data (e.g. number of known hotspots) is limited. A better method of validation is a survey that uses the predictive model to indicate hotspots of road-kill or connectivity blockages on a section of the road network that was not use to generate the data for the model development. Paired to the predicted hotspots should be a matched set of random locations in the regions of the predicted hotspots. In the validation phase, the tested hypothesis would be that predicted hotspots have higher densities of road mortality or serve as more important movement barriers than random locations along the road network.

Note that it would be possible with a hotspot model to predict coldspots – locations for which road-kill densities are lower than average or that are the least severe barriers for movement. One could validate by surveying matched pairs of predicted hotspots and coldspots. However, this would be risky, in my opinion, since a significant difference in road-kill densities between predicted coldspots and hotspots could be merely due to the model being successful at predicting coldspots, while performing little better than chance at predicting hotspots.

(7) Adaptive modification of the model.

Even if the model proves to be accurate at predicting hotspots, there is likely to be residual error: predicted hotspots that are no more severe than chance, and sites that are not predicted to be hotspots that in fact are. It is important to evaluate how correctly predicted hits (hotspots) differ from false alarms, and how misses (locations predicted not to be hotspots that in fact are) differ from correctly predicted non-hotspot locations. Based on any insight gained from this analysis of residual error, the model can be modified and again validated on a new road network.

Method 1: Modeling Animal Movements

One method of creating a predictive model of road-kill hotspots or key sites for connectivity involves collecting data on movement patterns of individuals of target species in relation to roads, then using these data to simulate animal movements in other roaded landscapes. By simulating movements of many individuals, one could predict segments of road where animals would be most likely to attempt to cross, or else segments where they would cross if not deterred by the road or road traffic. Using the predicted spatial patterns of road-crossing, one could further model the risk of road mortality to animals crossing at each road segment, and thus spatial patterns of road-kill.

High-resolution measurement of movement patterns of individuals in real roaded landscapes is typically done via intensive radio-telemetry. This method is expensive and time-consuming, and only feasible for sampling a limited number of individuals over a small proportion of a road network. Radio-telemetry of individual reptiles and amphibians can potentially reveal not only where individuals are likely to cross, but also where animals are deterred from crossing (Shepard et al. 2008, Beaudry et al. 2009). This latter information is critical for locating choke-points on population connectivity.

To create a model of critical sites along roads for road mortality and habitat connectivity:

(1) Typical movement trajectories are modeled using data on patterns of actual animal movements generated from radio-telemetry or other methods: e.g. over what land cover individuals of a species prefer to move, how far they travel during long movements between habitat patches, how straight and direct are movements between patches (e.g. for two turtle species, see Beaudry et al. 2009).

(2) The locations of the primary resource patches between which animals move are accurately mapped using GIS in relation to roads. Depending on the taxon, the relevant resource patches may include breeding sites, foraging habitat, and hibernacula (e.g. for vernal pools used as breeding sites for vernal-pool breeding salamanders, see Compton et al. 2007).

(3) Movement trajectories between resource patches of virtual animals are simulated, using the modeled trajectories in Step 1 and the resource patch maps in Step 2. The simplest models are 'gravity models' which model trajectories that are 'least-cost' in terms of distance traveled between patches, with some cutoff for distances that are considered too long to be feasible for the modeled species. An added feature can be to rank the quality of resource patches, and thus simulate trajectories that are a compromise of minimizing the cost of travel while maximizing the quality of the resource patch that is traveled to (e.g. for turtles, see Beaudry et al. 2009).

An even more detailed approach is to incorporate landscape resistance, in terms of different travel cost coefficients for traversing different land uses or crossing roads. For the purposes of modeling movement trajectories, these cost coefficients are based on how they affect animal behavior – how willing individuals of the modeled species would be to traverse habitat of each resistance class. Although ideally resistance coefficients are generated directly from behavioral data, they may also be inferred via 'expert opinion' (e.g. Compton et al. 2007). Similar to simpler gravity models, one models trajectories that are 'least-cost' in terms of the product of distance and the resistance coefficients of the landscape traversed (e.g. for toads see Joly et al. 2003, for vernal-pool breeding salamanders see Beaudry et al. 2009).

(4) For species that are deterred by roads or road traffic, one could create matched simulations of animal movement trajectories with and without roads. Variable road resistance depending on road size and traffic volume could be encoded via different resistance coefficients depending on classes of size and volume. Comparing simulations, locations for which movement trajectories frequently cross in the road-less simulation but are rarely traversed in the roaded simulation are potentially excellent candidates for passageways or other methods to preserve or restore habitat connectivity.

(5) For species that readily attempt to cross roads when traversing between resource patches, the spatial patterns of road crossing produced in Step 3 can be converted into a density of road-kill using standard models of road-kill risk. These models use traffic volume and speed of animal movement when crossing roads to estimate risk (e.g. Gibbs and Shriver 2002, 2005; Litvaitis & Tash 2008). Thus, hotspots of road-mortality are predicted as a function of how frequently animals attempt to cross at each road segment and the probability that crossing animals are killed by vehicle traffic at the segment. The relative severity of hotspots could then be ranked to provide a priority ranking for monitoring and mitigation.

(6) Validation would include monitoring movement patterns of animals in the vicinity of the predicted connectivity blockages caused by roads as indicated in Step 4, or measuring road-kill densities at predicted hotspots as indicated in Step 5, and comparing these to random segments of road within the network.

(7) Assuming that the model is confirmed as predictive, residual error should be evaluated. For example, what features are associated with predicted hotspots that in fact have little road mortality vs. predicted hotspots that (as predicted) do have high mortality? What features are associated with segments predicted to have few road-kill that in fact are hotspots, vs. those for which (as predicted) road mortality is not severe.

(8) Revise the model using the results of Step 7, and again validate it on a new road network. Repeat Step 7 and Step 8, should further improvement of the predictive accuracy of the model be desirable and judged feasible.

The disadvantages of attempting via simulations of animal movements to infer hotspots of road-kill or blockages to habitat connectivity caused by roads and road traffic include the difficulties of (1) gathering enough movement data on animals to accurately infer how movement trajectories are affected by land use, road presence, traffic volume, and distribution of resources, i.e. the data necessary to generate valid cost functions, and (2) assembling accurate data at a useful spatial scale on land use, resource patch quality and other factors required to create a valid 'resistance surface' throughout the road network.

Moreover, given the logistical challenges of collecting adequate animal movement data, this method is only suitable for studies focused on one or a very few species of reptile or amphibian. It is only suitable for locating herpetofauna hotspots in general in the case that the focal species movement patterns indicate movement patterns of the wider community of reptiles and amphibians in the landscape; this may be true for wetland-associated reptiles and amphibians, whose road-kill hotspots overlap (Langen et al. 2009).

The advantages of modeling animal movements as a tool to identify road-kill hotspots include that the simulations can be used to predict not only where road-kill hotspots currently occur, but also locations where road-kill was likely high in the past but is now low because local populations of the modeled species have been reduced by excessive road mortality. The method can predict road-kill hotspots and connectivity blockages of proposed new road routes, so that route modifications or prospective mitigation can be incorporated early in the road planning stage.

Unlike other methods, by modeling animal movements, it is not necessary rely on observed spatial patterns of road mortality to develop the hotspot model. Some road managers may be tempted to infer that road segments with few road-kill are benign, when some of these segments may in fact be severe barriers to connectivity. By modeling animal movements, one can distinguish low road-kill road segments that are unimportant as movement corridors from those that are critical connectivity blockages.

So far, studies that have modeled animal movements in relation to roads have done this mainly as an exercise to estimate regional population viability as impacted by road-kill and reduced habitat connectivity, or else to show how well the method works at predicting crossing patterns at specific road segments. In one of the most thorough studies, Beaudry et al (2003) identified spatial patterns of road crossing for two threatened species of turtle, but found that the predicted crossing hotspots were too broad and too numerous to feasibly mitigate via barriers and passageways. Although this modeling method is promising, I am not aware of any study that has yet tried to use it to predict the location of hotspots or connectivity blockages throughout a large road network, and then tested the predictions to evaluate the utility of it as a network-wide predictive tool.

Method 2: Creating Models Based on Point-Transect Data

Point-transect surveys are short fixed-length segments of road that are sampled intensively for road-kill. Walked point-transects are appropriate when road-kill cannot be reliably detected from a moving vehicle because of small size. Point-transect surveys are suitable as a survey methodology when road-kill is dense, such that remains of multiple individuals are likely to be encountered, at least at hotspots of mortality. Langen et al. (2007), for example, found that amphibians were not reliably detected via driving surveys, but multiple individuals could be detected by walking 100 m segments of road.

To create predictive models of road mortality hotspots, point-transects at known hotspots and at randomly or uniformly-distributed locations can be surveyed. Road, local features, and larger landscape features can then be evaluated as putative predictors of road mortality hotspots using presence/absence of road-kill at point-transects, or the actual number of road-kill recorded at each transect.

To create a model of road mortality hotspots using point-transect data:

(1) Preliminary methodological validation is required to determine the appropriate length of point-transects. Point-transects should be long enough that road-kill is likely to be detected at locations where road mortality is relatively high. Preliminary validation of the survey methodology should also assess the timing of surveys, to optimize the probability of detecting road-kill. Furthermore, it is necessary to quantify the ranked repeatability of point-transect counts, to determine whether multiple resurveys of each point-transect are necessary to accurately rank the relative density of road mortality among surveyed locations. For an example, see Langen et al. (2009).

(2) A sampling protocol for spatially distributing point-transects along surveyed roads must be specified. Point-transects should be distributed throughout a section of road network that is representative of the wider road network for which the model is intended to apply. An adequate number of point-transects is determined by the likelihood that some point-transects will be located within road-kill hotspots. If hotspots are small in spatial extent and few in number along a road network, many randomly or uniformly-spaced point-transects may be required to insure that enough are encountered that the predictive hotspot model can be created. If some hotspot locations are known prior to conducting a survey, they can be included, and fewer random point-transects will be necessary.

In addition to including any known hotspots within a survey, I advocate uniformly-distributed locations over random locations for point-transects. A uniform distribution of survey locations helps to insure that there will be adequate spatial dispersion of samples throughout a surveyed road network.

One methodological problem is that spatially-nearby point-transects are usually surveyed close in time, as a logistical convenience of surveying routes. If so many points are to be surveyed that there is a risk that average road-kill densities will vary over the time-course of a survey period, there must be some methodological measures taken to reduce the risk that spatial and temporal trends are confounded. This may include repeating point-transects in varying temporal order, or clever routing of the survey to minimize the risk that temporal autocorrelation is confounded with spatial autocorrelation. The temporal autocorrelation problem is particularly problematic for amphibian surveys, because amphibian movements are so weather and microclimate dependent and because road-kill amphibians disappear so quickly from the roadway. For a discussion of methodological considerations pertaining to point-transect surveys, see Langen et al. (2007, 2009).

(3) A database of features that are potentially predictive of road-kill density around point-transects must be assembled. Such features could include road attributes (e.g. traffic volume, road configuration, bordering vegetation), land use and land cover at a series of spatial scales around the point, hydrology and topography, and locations and quality of key resource sites that are the target of animal movements (e.g. wetlands, nesting sites). Some features may be noted in the field during a survey, whereas others can be acquired by analyzing GIS data coverages of relevant features.

(4) A valid method of exploratory statistical analysis must be selected to create a useful predictive model. Modeling to evaluate potential predictors of road mortality hotspots based on point-transect data typically is done using stepwise general linear modeling, using a valid method of exploratory model evaluation such as AIC. Depending on the distribution of road-kill counts among point-transects, the dependent variable may either be presence vs. absence of road-kill, if many locations have zero road-kill recorded, or else the number of road-kill per point transect, if the distribution of counts is more continuous. The relative predictive strengths of models are compared, the accuracies of the best predictive models are evaluated, and the relative importance of each potential predictor is determined. A model selected for validation should be one that is accurate at discriminating road-kill hotspots from other point-transects, and uses predictors for which data can be acquired easily on all roads for which hotspots are to be predicted using the model.

(5) A validation study must be done to evaluate the usefulness of the predictive model. Validation is straightforward: use the candidate best predictive model to predict hotspots of road-kill in a comparable road network to the one used to create the model, and survey those predicted hotspots and a comparable set of random locations.

(6) Assuming that the model is confirmed as predictive, evaluate the residual error. What features are associated with predicted hotspots that in fact have little road mortality vs. predicted hotspots that (as predicted) do? What features are associated with random locations that have severe road mortality present, vs. those that (as predicted) are not severe?

(7) Revise the model using the results of Step 6, and again validate it on a new road network. Repeat Step 6 and Step 7, should further improvement of the predictive accuracy of the model be desirable and judged feasible.

An advantage of using point-transects for modeling is that it is relatively easy to collect road-kill data, and point-transects are a valid methodology for estimating road-kill densities. Patterns of road-kill of all reptile and amphibian species can be collected at the same time using this method. It is straightforward and easy to create predictive models of road-kill hotspots using point-transect data, and validation is also straightforward and easy. A disadvantage of walked point-transects is that much less of a roadway can be surveyed during a specified period of time than would be using a driving survey methodology.

A second disadvantage is that point-transects of road-kill are useless at detecting sites where animals are deterred from road-crossing, and thus critical blockages to connectivity caused by road avoidance cannot be directly detected by this method. A related disadvantage of the point-transect method is that it will not detect sites that were formerly road-kill hotspots but are no longer because populations in the vicinity have declined due to past excessive road mortality.

One possible way to overcome these disadvantages would be to conduct the surveys to be used to create the hotspot model in a region where abundant and well-connected habitat, low traffic volumes, and low road density make population declines near roads and road deterrence unlikely. A predictive model created in such a region could be used to predict road-kill hotspots in a region where road densities and traffic volumes are higher, and habitat is scarcer and more fragmented. Road segments for which the model predicts a road-kill hotspot but observed road-kill density is low would raise suspicion that populations bordering the road have declined due to past unsustainable road-kill, or else animals are deterred from crossing.

Case History

As reported in Langen et al. (2009), my students and I surveyed 145 point-transects throughout a 353 km highway network in northeastern New York State, USA for road-kill of reptiles and amphibians. These points included 137 evenly distributed points throughout the network and 8 previously-identified road-kill hotspots. We used 100 m walked point-transects as the method of road sampling, because we previously had found that amphibians could only be validly quantified as road-kill using walked transects (Langen 2007). We used land cover at four spatial scales (50 m, 100 m, 500 m, and 1000 m around the point transect), wetland configuration, and traffic volume to identify features that best predicted hotspots of herpetofauna road mortality. Forty points were resampled an additional 4 times over 4 years to evaluate temporal repeatability of point-transects. We created general linear models predicting presence or absence of road-mortality at point-transects, and evaluated both models and individual putative predictors using AIC.

Both amphibian and reptile road mortality were spatially clustered, and road-kill hotspots of the two taxa overlapped. A single survey provided a valid snapshot of spatial patterns of road mortality, and spatial patterns remained stable across time. Road-kill hotspots were located where wetlands approached within 100 m of the road, and the best predictor was a causeway configuration of wetlands (wetlands on both sides of the road within 100 m of it).

We validated causeways as predictors of road mortality by surveying 180 causeways and 180 random points across five regions (17,823 km^2) of northeastern New York. Causeways were 3x more likely than random locations to have amphibian and 12x more likely to have reptile mortality present, and causeways had a 4x higher total number of amphibian road-kill and 9x higher reptile road-kill than random points. Residual errors were due to inaccuracies in the wetland maps used to identify causeways, and due to including as random points locations that, although not causeways, were adjacent to one large wetland. We concluded that it is possible to identify valid predictors of hotspots of amphibian and reptile road mortality for use when planning roads or when conducting surveys on existing roads to locate priority areas for mitigation.

Method 3: Creating Models Base on Road-Kill Records

The traditional way to identify wildlife road mortality hotspots is via road-kill records; this method has been used primarily to analyze spatial patterns of mammalian road-kill (e.g. Smith 1999, Joyce and Mahoney 2001, Clevenger et al. 2002, 3003, Ramp et al. 2005, Seiler 2005). This method requires a database of accurately-mapped road-kill assembled either from planned road surveys or from ad hoc records collected by law enforcement, road managers, or other sources.

This method is only appropriate for animals that are easily detectable while driving a road, and for which road-kill densities are too low to survey via walked point-transects. To create predictive models of road mortality hotspots using road-kill records, clusters of road-kill are identified using spatial statistics and GIS, and the potentially-predictive attributes of the locations of the road-kill clusters can be compared to a randomly-selected set of locations that are outside of any cluster. Alternatively, attributes around road-kill sites can be compared to a randomly-selected set of locations where no road-kill was ever detected.

To create a model of road mortality hotspots using road-kill records:

(1) Preliminary methodological validation is first required to determine whether targeted reptile and amphibian species are detectable from a moving vehicle. Langen et al. (2007) for northeastern New York State and unpublished data from Costa Rica indicate that slow-speed (less than 40 km/h) driving surveys are adequate for detecting turtles and medium-sized snakes and lizards, but are poor for detecting amphibians and small reptiles. As discussed in Langen et al. (2007), the accuracy of driving surveys at detecting road-kill can be assessed by both measuring inter survey-team repeatability of road-kill detections, and by comparing data collected from road surveys with that of point-transect data collected along the same road network.

Preliminary validation of the survey methodology should also assess the timing of surveys (time of day and season) to optimize the probability of detecting road-kill, and the optimal frequency of repeating surveys. In my experience, except for turtles, reptile and amphibian road-kill disappear quickly from roads, and becomes undetectable via driving surveys within a day.

(2) A valid sampling protocol for driving surveys must be planned. The valid road survey must include (a) a selection of roads that is representative of the characteristics of the wider road-network for which hotspots are to be predicted and (b) a survey route and protocol that results in equal sampling effort and road-kill detectability on all surveyed roads.

Most problematic is when survey effort among roads varies (i.e. some roads are driven more frequently than others), detectability is variable among road segments (e.g. when driving speed varies depending on the road speed-limit), and persistence of road-kill on roadways varies among roads (e.g. when road-kill on high traffic volume roads disintegrates more rapidly, or road-kill on low volume roads is removed more rapidly by scavengers). Presence of any of these biases may result in spurious spatial patterns of road-kill; it may be necessary to correct for these biases before attempting to identify legitimate road-kill hotspots.

(3) Once a sufficient number of road-kill records are assembled, an analysis of the spatial patterns of road mortality can be made. Popular methods include kernel density analysis at a specified road segment length to identify dense aggregations of road-kill, and Ripley's K analysis at a variety of spatial scales to identify the spatial scale of road-kill aggregations (e.g. Clevenger et al. 2003, Ramp et al. 2005). The latter is useful for identifying the length of typical hotspots, which is a key consideration when evaluating mitigation options.

(4) A database of features that are potentially predictive of road-kill hotspots or individual road-kill sites must be assembled. Such features could include road attributes (e.g. traffic volume, road configuration, bordering vegetation), land use and land cover at a series of spatial scales around the point, hydrology and topography, and locations and quality of key resource sites that are the target of animal movements (e.g. wetlands, nesting sites). Some features may be noted in the field during a survey, whereas others can be acquired by analyzing GIS data coverages of relevant features.

(5) Similar to the point-transect method, a valid method of exploratory statistical analysis must be used to create a useful predictive model. This is typically done using stepwise general linear modeling, using a valid method of exploratory model evaluation such as AIC. The dependent variable in such analyses is dichotomous: either road-kill cluster vs. random location or else road-kill record versus no road-kill location. The relative predictive strengths of models are compared, the accuracies of the best predictive models are evaluated, and the relative importance of each potential predictor is determined. A model selected for validation should be one that is accurate at discriminating road-kill hotspots from other segments of roadway, and that uses predictors for which data can be easily acquired before a survey to predict where road-kill hotspots occur within a road network.

(6) A validation study must be done to evaluate the usefulness of the selected putative best predictive model. Validation is straightforward: use the candidate best predictive model to predict hotspots of road-kill in a comparable road network to the one used to create the model, and survey those predicted hotspots and a comparable set of random locations.

(7) Assuming that the model is confirmed as predictive, evaluate the residual error. What features are associated with predicted hotspots that in fact have relatively little road mortality vs. predicted hotspots that (as predicted) do? What features are associated with random locations that have severe road mortality present, vs. those that (as predicted) are not severe?

(8) Revise the model using the results of Step 7, and again validate it on a new road network. Repeat Step 7 and Step 8, should further improvement of the predictive accuracy of the model be desirable and judged feasible.

An advantage of using road-kill locations for modeling is that it is relatively easy to collect road-kill data, and there is a large body of research on how to analyze the spatial dispersion of road-kill to locate hotspot clusters. Moreover, a much larger expanse of road can be surveyed via driving surveys than can be monitored with radio-telemetry or surveyed using walked point-transects.

One disadvantage of using road-kill records is that collecting the data via driving surveys is time-consuming, potentially hazardous, and sometimes expensive since roads may need to be driven many times to acquire adequate numbers of road-kill records for analysis. Another disadvantage is that there is a detection bias toward detecting large individuals; this is potentially a serious problem if smaller-sized individuals, typically younger age-classes, are not reliably detectable and have different movement patterns with respect to roads than larger.

Unlike animals for which vehicle collisions cause human injuries and property damage (e.g. ungulates), there is unlikely to be an existing database of road-kill locations of reptiles and amphibians. Those road-kill records that may exist (e.g. state heritage program databases and herpetofauna atlas records) are unlikely to provide a sufficiently unbiased sample of spatial road-kill patterns.

A second disadvantage of creating hotspot models using road-kill data is that these data are useless at detecting sites where animals are deterred from road-crossing, and thus critical blockages to connectivity caused by road avoidance cannot be directly detected by this method. Moreover, the method will not detect sites that were formerly road-kill hotspots but are no longer because populations in the vicinity have declined due to past excessive road mortality.

One possible way to overcome these disadvantages would be to conduct the driving surveys in a region where abundant and well-connected habitat, low traffic volumes, and low road density make population declines near roads and road deterrence unlikely. A predictive model created in such a region could be used to predict road-kill hotspots in a region where road densities and traffic volumes are higher, and habitat is scarcer and more severely fragmented. Road segments for which the model predicts a road-kill hotspot but observed road-kill density is low would raise suspicion that populations bordering the road have declined due to past unsustainable road-kill or else animals are deterred from crossing.

Case History

In a currently unpublished study, my colleagues and I conducted weekly driving surveys over a two-year period of a 160 km circuit of highway in northeastern New York State, and recorded the location of 162 turtles of three species (*Chelydra serpentina*, *Chrysemys picta*, *Emydoidea blandingii*). Driving surveys were used because we had previously found that this method was valid for detecting road-killed turtles, and that the road-kill density of turtles was too low to detect via short walked point-transects (Langen et al. 2007). We used these data on spatial locations of road-kill turtles to analyze the spatial dispersion and the road and landscape features associated with the road-kill locations. We used spatial statistical methods to identify the degree of aggregation of turtle road-kill, and the spatial extent, severity, and location of clusters of mortality. We compared traffic volume, wetland size and configuration, and surrounding land use (100 m around a point) at turtle road-kill records to random points at least 200 m distant from road-kill, and evaluated both models and individual putative predictors using AIC. For causeways, defined as road segments with wetlands within 100 m on both sides of the roadway, we also created general linear models predicting presence or absence of road-mortality, and again evaluated both models and individual candidate predictors using AIC.

Road-kill was aggregated at causeways that were greater than 200 m in length and characterized by high traffic volumes, close proximity to water, and high forest coverage near the road. The locations of road-kill aggregations, as indicated by kernel density analysis, and the peak spatial extent of aggregations (250 m) as indicated by Ripley's K, corresponded to the locations and average lengths of causeways. We concluded that most freshwater turtle road mortality along northeastern New York State highways is spatially aggregated at short, severe hotspots, and these localities occur at predictable features along or adjacent to a road network. Thus it should be possible to efficiently and precisely locate sites of highest risk of turtle road mortality when the location of wetlands near roads, road traffic volumes, and the land-cover / land-uses bordering the roads are known. Moreover, standard spatial statistical methods used to investigate patterns of road-kill are successful at indicating the location and spatial extent of road-kill hotspots, and can be used to assist in determining the spatial scale and key road and landscape features associated with road-kill clusters. The next step to this project, yet to be initiated, is to validate our best predictive model along other regional road networks.

General Conclusions and Recommendations

All three hotspot modeling methods are promising – each has been used to successfully predict hotspots of road-kill or critical connectivity corridors for a few reptile and amphibian species on some limited stretches of roadway. However, I am not aware of any study that has used a model created by any of these three methods to predict hotspots throughout a large road network, as has been done for mammals (e.g. along the highways of Florida USA, see Smith 1999). In my opinion, a critical next-step in management of road impacts on reptiles and amphibians will be to use a validated model to predict road-kill hotspots or key connectivity linkages throughout a road network, and then devise a plan to implement monitoring and mitigation at the network's highest priority hotspots.

A valid predictive model will also be of great use for estimating how much of a road network is encompassed by hotspots. In the two case studies I reviewed in this paper, causeways were identified as key predictors of road-mortality hotspots. This is not too surprising, since nearly all of the reptile and amphibian species in northeastern New York are wetland-associated. Using the New York State Department of Environmental Conservation Regulatory Wetland Maps for each of the five ecoregions that I and my students surveyed in northeastern New York State, I quantified the fraction of the highway network that was within a causeway, as I defined this feature (i.e. roadway with matched wetlands on opposite sides of the road and each within 100 m of it). Among the regions that we surveyed, highway densities varied between 0.13 - 0.45 highway km / km^2 (this greatly underestimates total road density since these data exclude town, village, and private roads; only about 35% of roads within the region are highway). The average causeway length was 200 - 350 m, and the number of causeways ranged 10 - 43 / 100 km highway, for an average total extent of 26 - 133 m / km-highway.

During our fieldwork, we surveyed an average of 30 locations per workday. Thus, to survey all causeways in a highway network just once using our point-transect survey methodology, 70 - 301 km of highway (290 - 805 km^2 landscape) could be surveyed per day per survey-team in northeastern New York State. A filtering algorithm that incorporated additional predictors such as traffic volume and causeway length would increase the expanse of road that could be practically surveyed within a specified time period, by prioritizing surveys to the causeways that are predicted to be the most severe hotspots.

For most effective management, hotspots need to be spatially restricted in length, so that mitigation measures such as barriers, passageways, and signage are feasible and worthwhile. They need also be severe (have a much higher volume of animal passage or potential passage if unblocked than random locations), so that the impact of mitigation on local populations is sufficiently large. The length and severity of hotspots are a function of how canalized movements are when animals move between resource patches, and the fraction of animals within a local population that use a particular corridor.

Whereas hotspots for mammals are typically on spatial scales of kilometers, many of the most infamous road-kill hotspots for salamanders, frogs, and wetland-associated reptiles are less than 500 m length along a roadway (e.g. sites described in Langton 1989, Elzanowski et al. 2009). These notorious sites are typically either near communal hibernacula, causeways, or migration corridors between breeding sites and non-breeding home-ranges. Hotspot models such as I describe in this paper will be most useful as a tool for monitoring and mitigation for those reptile and amphibian taxa that use movement corridors that are spatially restricted. For some species, such as desert tortoises (Boarman and Kristan 2006) and tropical upland snakes (Langen, unpublished data), animals are much less spatially restricted in where they approach roads, and thus hotspot models may not be a useful tool for road management targeted at these species.

I conclude that hotspot models are a promising tool for environmental management of road mortality and connectivity blockages of reptiles and amphibians caused by roads and road traffic. Hotspot models may well be more effective management tools for reptiles and amphibians than mammals (the usual focus of these models), since herpetofauna hotspots often encompass a narrower length of roadway, are very severe, and are often highly associated with conspicuous landscape features such as wetlands or communal hibernacula. The locations of hotspots for many species of both reptiles and amphibians often overlap. A significant fraction of a local population of a reptile or amphibian species may attempt to cross a road at a hotspot; or would cross should it be unblocked. For such species, management of hotspots is an essential element of an effective conservation plan. Agencies and organizations concerned with the conservation of reptiles and amphibians should collaborate with researchers to (1) identify species that are negatively impacted by roads and for which the impacts are most severe at discrete spatial hotspots, (2) create and validate hotspot models for these species, and (3) develop best-practices that use the models as tools to locate priority sites for monitoring and mitigation.

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Biographical Sketch

Tom Langen is an Associate Professor at Clarkson University. His research focuses on the environmental impact of infrastructure and human land-use practices, including the environmental impacts of roads and the conservation value of wetlands reconstructed under public-private partnership programs. Road- related research in the northeastern US has included the environmental impact of deicing road salt on high-altitude soil and lakes, and methods of predicting and mitigating hotspots of herpetofauna road mortality. In Costa Rica, he is conducting research and leading courses and professional-development workshops on the impact of public roads on national parks and other protected areas in Central America.

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