# Predicting Hot Spots of Herpetofauna Road Mortality Along Highway Networks

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**ABSTRACT** Road mortality is often spatially aggregated, and there is a need for models that accurately and efficiently predict hot spots within a road network for mitigation. We surveyed 145 points throughout a 353-km highway network in New York State, USA, for roadkill of reptiles and amphibians. We used land cover, wetland configuration, and traffic volume data to identify features that best predicted hot spots of herpetofauna road mortality. We resampled 40 points an additional 4 times over 4 years to evaluate temporal repeatability. Both amphibian and reptile road mortality were spatially clustered, and road-kill hot spots of the 2 taxa overlapped. One survey provided a valid snapshot of spatial patterns of road mortality, and spatial patterns remained stable across time. Road-kill hot spots 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). We validated causeways as predictors of road mortality by surveying 180 causeways and 180 random points across 5 regions (17,823 km$^2$) of northeastern New York. Causeways were 3 times more likely than random locations to have amphibian and 12 times more likely to have reptile mortality present, and causeways had a 4 times higher total number of amphibian roadkill and 9 times higher reptile roadkill than did random points. We conclude it is possible to identify valid predictors of hot spots of amphibian and reptile road mortality for use when planning roads or when conducting surveys on existing roads to locate priority areas for mitigation. (JOURNAL OF WILDLIFE MANAGEMENT 73(1):104–114; 2009)

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Roads and road vehicle traffic can alter the demography of animal populations due to roadkill and reduce or eliminate connectivity between populations bisected by a road (Forman and Alexander 1998, Jackson 2000, Trombulak and Frissell 2000, Spellerberg 2002, Seiler and Helldin 2006). When designing new roads or managing existing roads, planners need to know where animals will attempt to cross so that mitigation practices can be implemented to reduce roadkill, which is particularly important for species that provide a hazard to motorists (e.g., ungulates) or for species that are likely to decline in population size due to excessive mortality caused by roadkill (e.g. mammalian carnivores). Similarly, there is a need for information on key linkages that should be managed to facilitate safe crossings to maintain population connectivity, especially for species that require such connectivity for long-term population viability (Jackson and Griffin 2000, Bank et al. 2002, Evink 2002, Forman et al. 2003, Brown 2006). Several recent studies have analyzed spatial patterns of roadkill in mammals and have successfully identified road characteristics and roadside environmental features that predict hot spots of mortality (e.g., Smith 1999; Clevenger et al. 2002, 2003; Ramp et al. 2005; Seiler 2005).

Reptile and amphibian populations are often lower in the vicinity of major roads and within landscapes with high road densities than populations in regions where roads are distant and few (e.g., Rosen and Lowe 1994, Fahrig et al. 1995, Vos and Chardon 1998, Marchand and Litvaitis 2002, Boarman and Sazaki 2006). These population declines may be due to any number of factors that are associated with presence of roads and roaded landscapes, but the most apparent impact of roads is increased mortality due to fatal injuries from collision with motor vehicles when crossing the road surface (Wright 2006, Andrews et al. 2007). Large numbers of reptiles and amphibians cross roads during seasonal migrations to and from hibernation or breeding sites, during natal or juvenile dispersal, and during movements between wetland and upland habitat or between wetlands (e.g., Bonnet et al. 1999, Pope et al. 2000, Hels and Buchwald 2001, Steen et al. 2006, Langen et al. 2007). Some reptiles and amphibians also may be attracted to road surfaces for thermoregulation (Dodd et al. 1989, Rosen and Lowe 1994, Shine et al. 2004). At certain localities, the numbers killed can be enormous (e.g., Ashley and Robinson 1996, Hels and Buchwald 2001, Smith and Dodd 2003, Aresco 2005*b*, Langen et al. 2007).

Road mortality or the barrier effect of roads can alter demographic and genetic structures of reptile and amphibian populations (Reh and Seitz 1990, Lesbarrères et al. 2003, Steen and Gibbs 2004, Row et al. 2007). Landscape models of animal movements within existing road networks predict that regional declines of some reptile and amphibian populations are likely unless effective technologies and best practices to reduce road mortality and maintain connectivity are implemented throughout a road network (Gibbs and Shriver 2002, 2005; Roe et al. 2006; Compton et al. 2007). Because herpetofauna road mortality typically seems to be spatially aggregated, it should be possible to identify factors that are most strongly associated with road-kill hot spots and thus provide a tool for road planners and environmental managers to use for efficient and accurate location of sites to

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avoid or to implement mitigation practices when designing and managing roads.

In northeastern New York State, Langen et al. (2007) surveyed reptile and amphibian road mortality along a 353-km rural highway network and found that most roadkill was spatially clustered. We used this survey data and data on roadside land-use and traffic volume to identify putative predictors of road mortality hot spots of reptiles and amphibians. We also estimated the temporal repeatability of spatial patterning of roadkill, as indicated by repeated sampling of the same set of locations over a 4-year period. Finally, we test the validity of our putative best predictor of spatial patterns of road mortality by analyzing data from 9 surveys conducted among 5 regions of northeastern New York that were designed to compare predicted hot spots to random points along the road network.

We had 2 principal objectives. First, we attempted to identify a simple-to-use and valid indicator of road mortality hot spots for use by road planners and environmental managers in our region. Second, we tried to develop a general methodology for creating and validating predictive models of spatial patterns of reptile and amphibian road mortality that can be applied elsewhere by road managers and environmental planners during road design or development of mitigation plans, in the same way that such models are currently being developed and used for mammals such as ungulates and large carnivores.

## STUDY AREA

In July 2002, we surveyed 145 points along the 353.3-km of federal, state, and county highways within 4 towns (975.4 km$^2$) in St. Lawrence County, New York State (75°15′N, 44°40′W; see Langen et al. 2007 for further details). Highways were 2-lane, except some short segments of additional lanes within 2 villages, and the roads were built at a slight elevation above the adjacent landscape. Average annual daily traffic (AADT) among surveyed roads was 451–13,968 vehicles/day (New York State Department of Transportation 2007; Ian Hazen, St. Lawrence County Highway Department, unpublished report); the speed limit on most stretches was 89 km/hour.

To validate our predictive model of herpetofauna road mortality hot spots derived from the 2002 survey, in 2006–2007 we surveyed points located at causeways (road segments with water on both sides of the road within 100 m of it) and random points along the state and county highway network of different ecoregions of northeastern New York State. Surveyed regions included 5 of 13 recognized ecoregions of New York State (ecoregions as defined in Levine 1998, and covering about half the surface area of NY), and a total surveyed area of 17,823 km$^2$ (13% of NY's land area, based on summed areas of the surveyed towns). The St. Lawrence Valley, Champlain Valley, and Great Lakes Plain ecoregions are all predominately lowland, flat, agricultural landscapes, whereas the Adirondack Mountains and Tug Hill are mainly highland mature forest. Population densities across these 5 regions ranged 4.6–30.8 people/km$^2$, and highway densities were 0.13–0.45 road-km/km$^2$. The mean length of causeways was 195.5–260.4 m, and there was an average of 0.1–0.4 causeways/road-km, thus 3–13% of the highway network was within a causeway zone as we defined it.

## METHODS

We surveyed 137 points that were distributed uniformly every 3.2 km throughout the highway network and an additional 8 points that had been identified as putative road mortality hot spots during a pilot driving survey. To begin a road survey, we went to the origin of a highway, or to the first stretch within the border of our study area, and we sited the first survey point at a random point within 150 m of the survey route starting point. Subsequent points were uniformly spaced 3.3 km apart along a road. We sampled the 8 predetermined points when we encountered them along a survey route. We surveyed $\geq 1$ point along every highway within the study area. We used a systematic sampling design rather than a random design to guarantee that the road network was thoroughly and evenly sampled; systematic designs have some advantages and few disadvantages relative to a random design, except in the highly unlikely event of periodic spatial patterns that correspond to the sampling interval (Krebs 1999). We included the additional 8 known hot-spot points because of the risk that our sampling design might result in no samples at road-kill hot spots, should these be rare and small in expanse.

We surveyed each point once. We conducted surveys on 7 dates during a 10-day period in July (10–19 Jul 2002), with 18 ± 4.3 (SD) points per survey date. We surveyed on weekdays, when traffic was highest, during mornings (0530–1130 hr). On each survey date, 2 teams surveyed different regions of the road grid. Weather conditions, which can dramatically influence activity patterns of herpetofauna, were similar during all of the survey dates (daily high temp = 25 ± 2.6 [SD]° C, range 21–28; low temp = 12 ± 3.4° C, range 7–15; no precipitation on any sample dates).

Sampling sequentially along a route can introduce a bias in detecting spatial patterns, because spatially near points are sampled close in time. Although admittedly a possibility, we judge it unlikely to be important in our study, given that weather conditions were similar across the study period, we sampled >1 region a day, and there were no spatial patterns across sample days pertaining to the sections of the road grid that we sampled. Initial preliminary data analyses did not indicate any patterns in road-kill abundance associated with sample date or time during the study period. Relative abundance of road-kill among points was repeatable across time, and the correlation between the relative abundance of road-kill among points on this survey and the average of 4 subsequent surveys was high (see Results).

At each survey point, we delineated a 50-m transect and walked in each direction from the center point, for a total road transect length of 100 m. Survey points at the 8 predetermined hot spots were located at the presumed center of each. Surveyors walked each side of the road and tabulated any dead reptile or amphibian. Intersurveyor reliability of road-kill counts was high (Langen et al. 2007). Surveyors noted the precise location of each survey point using a Global Positioning System (GPS) with a Wide Area Augmentation System correction (spatial accuracy typically ± 5 m).

We used the Geographic Information System (GIS) application ArcGIS 8.2 to measure land use surrounding survey points. Each point was located on a georeferenced map of the highway network, and we characterized land cover around it from the United States Geological Survey National Land Cover Data Set (USGS NLCD; 30-m resolution of 21 land cover categories, derived from 1992 satellite imagery). Although there may have been some land use changes between 1992 and the 2002 survey period (see Discussion), the land use patterns indicated in the 1992 USGS NLCD generally seemed to correspond with what we observed on the ground.

To quantify land cover, we drew a buffer of a specified radius around each point and quantified proportional representation of each color-coded land cover class within the circle using imaging software (ImageJ; National Institutes of Health, Bethesda, MD). To determine the best spatial scale for relating land cover to herpetofauna road mortality, we used 4 buffer sizes (50-m radius = 0.8 ha, 100-m radius = 3.1 ha, 500-m radius = 78.5 ha, and 1,000-m radius = 315.3 ha).

Of the 21 possible land cover classes 13 were represented in the data for the survey points (see United States Environmental Protection Agency [2007] for definitions of the 1992 NLCD land cover classes). One class, quarries and mines, accounted for <0.5% of coverage at any spatial scale, and we did not include it in subsequent analyses. Preliminary data analyses using factor analysis via principal components indicated that the 12 intercorrelated categories could be collapsed into 6 independent composite categories of related land cover classes (principal components extracted using varimax transformation, overall significance of factor analysis model: Bartlett's $\chi^2_9 = 593.2$, $P < 0.001$). As justified by the factor loadings and for simplicity and ease of interpretability, we created composite categories by directly combining the raw scores of the classes rather than using the factor scores. Results did not qualitatively differ whether we used combined raw scores or the factors. The 6 composite categories were 1) wetlands, including open water (1992 NLCD class 11), woody wetland (class 91), and emergent herbaceous wetland (class 92); 2) forest, including deciduous forest (class 41), evergreen forest (class 42), and mixed forest (class 43); 3) row crops (class 82); 4) pasture or hay field (class 81); 5) residential, including low density residential (class 21) and high density residential (class 22); and 6) commercial, including industrial or commercial development (class 23) and parks, lawns, transportation corridors, and golf courses (class 85).

We estimated relative road traffic volume at each survey point by using AADT data from the most recent (within 5 yr) and nearest traffic volume monitoring location (<5 km) on the same highway (New York State Department of Transportation 2007; Ian Hazen, unpublished report). Transportation agencies estimate AADT via periodic (annual or less frequent) short duration traffic counts that are then applied to a predictive statistical model. Thus, AADT provides an indicator of relative traffic volume among surveyed highways but is not an actual measure of the traffic volume on the date of a survey. Data on hourly traffic patterns within a day along one surveyed highway is shown in Langen et al. (2007).

We used logistic regression to evaluate the 6 composite land cover categories and AADT as predictors of presence or absence of herpetofauna road mortality at survey points (models generated using JMP 7.0; SAS Institute, Cary, NC). We generated separate sets of logistic regression models for each spatial scale of land cover (50 m, 100 m, 500 m, and 1,000 m). For each spatial scale, we used an exploratory approach analogous to forward and backward stepwise regression. We evaluated relative fit of models using an information–theoretic approach to model selection based on Akaike's Information Criterion adjusted for small sample size ($AIC_c$; see Burnham and Anderson 1998, Motulsky and Christopoulos 2004). First, we generated a saturated model (one that included all 7 putative predictor variables). Then, we removed the predictor variable whose absence resulted in the largest decrease in $AIC_c$. We continued removing variables in succession, until removal of any additional variable resulted in a higher $AIC_c$. Second, we added the single variable whose presence most reduced $AIC_c$ from the null (intercept) model. We then successively added the next variable that most decreased $AIC_c$, until addition of any variable resulted in a higher $AIC_c$. The forward and backward approaches identified the same best model. To identify the best spatial scale for analysis, we compared the null (intercept) model, the saturated (all variables included) model for each spatial scale, the overall best model (as identified by the stepwise exploratory approach) for each spatial scale, and the best model restricted to one predictor for each spatial scale. We summed the Akaike weights of the 3 models at each spatial scale (best and saturated models; method adapted from Burnham and Anderson 1998), which we used to assess relative support for each spatial scale.

### Reanalysis of Predictors of Road Mortality at the Best Spatial Scale

We conducted a more detailed reanalysis of potential predictors of reptile and amphibian road mortality at the best spatial scale (100 m), as indicated by the first set of logistic regression models (see previous section). We had an insight based on field observations that wetland configuration in relation to the road may provide an additional predictor. To classify points based on wetland configuration, we used the New York State Department of Environmental Conservation Regulatory Freshwater Wetlands (NYSDEC RFW) map, which indicated wetlands ≥5.0 ha in surface area. These maps were drawn at a 1:24,000 scale based on aerial photos, published maps, and ground-truthing. For our study area, the original map was drafted in 1987, with amendments in 1998. We classified survey points as to presence of large wetlands ($\geq$5.0 ha) within 100 m of the road, as indicated on the NYSDEC RFW map, using the following categories: causeways (paired wetlands on opposite sides of the road within 100 m of it, 10% of points), adjacent wetlands (wetland on one side of the road within 100 m, 6% of points), or no wetland present (84% of points). Only a part of a wetland needed to be within the 100-m buffer for it to qualify as a component of a causeway or as an adjacent wetland.

We then evaluated models of presence or absence of herpetofauna road mortality at the 145 points using the same set of 7 putative predictor variables (6 land cover categories and AADT) plus wetland configuration. We coded wetland configuration as causeway or not causeway. Thus, not causeway included points that had no large wetland present or had large wetlands on only one side of the road. We used a similar exploratory approach to logistic regression modeling as before (see previous section). We retained for comparison all models that fit nearly as well as the best model (difference in $\text{AIC}_c < 2$) and then compared these models, all 8 models with one predictor variable, the saturated model (all 8 putative predictors included), and the null (intercept) model. For each of the 4 variables that were included in the best models, we summed the Akaike weights of all models in which the variable was included (method adapted from Burnham and Anderson 1998), and we assessed relative importance for each of the 4 variables.

### Temporal Repeatability of Road Mortality Spatial Patterns

To evaluate how well one survey indicated spatial patterns of road mortality, and to evaluate whether spatial patterns of road mortality detected in the initial (Jul 2002) survey remained repeatable across time, we selected for resurvey from the 145 points of the initial survey the 20 points that had the highest tallies of amphibians or reptiles and a random set of 20 points that had had no road mortality. We resurveyed the 40 points an additional 4 times over the next 4 years (Jul 2004, Jun 2006, Jul 2006, and Aug 2006), using the same methodology as the original survey. To measure how representative each survey was at indicating a point's overall relative ranking, we calculated the Spearman rank correlation between road mortality detected at each survey period against the summed number of road-kill detected during the other 4 surveys. To assess changes across time, we assessed temporal trends in pairwise Spearman rank correlations versus time between surveys (10 pairs, intervals 1 month to 49 months). This analysis was akin to an autocorrelogram, albeit with a nonparametric measure of association rather than an autocorrelation coefficient because of the non-normal distribution of the data caused by many low counts (0s, 1s, and 2s).

### Validating Causeways as Predictors of Hot Spots

The initial survey indicated that causeway presence or absence was the best predictor of herpetofauna road mortality (see Results). To validate the predictive value of causeways as hot spots of amphibian and reptile road-kill, we conducted 9 surveys in 2006 and 2007 within 5 regions within northeastern New York State. Our objective was only to test the validity of causeways as predictors of hot spots across the range of geographic and ecological conditions within northeastern New York. The focus of the sample design was a comparison of road-kill abundance at causeways versus random locations within each survey. The study was not intended to assess regional or temporal variation in road-kill abundance, both of which were very likely to be high, so we made no attempt to intersperse surveys in a way that would permit valid inferences about regional or temporal trends.

Using ArcGIS 8.2, before each survey we located 20 causeways (paired wetlands on opposite sides and within 100 m of the road) along county, state, or federal highways, using the NYSDEC RFW maps, which indicate wetlands $\geq$5.0 ha in surface area (within the Adirondack Park, the NYSDEC RFW includes smaller wetlands; for consistency, we only included causeways having both wetlands $\geq$5.0 ha). Only a part of a wetland needed to be within the 100-m buffer for it to qualify as a component of a causeway. We also selected 20 random points interspersed among the same segments of highway as the causeways (random points created using Hawth's Analysis Tools 2.0; SpatialEcology.com 2007). Random points included points that had wetlands on one roadside within 100 m but excluded causeways. We then located the 40 points in the field using a GPS. We surveyed each point using the standard 100-m walking transect protocol described in the Methods section.

We conducted 2 surveys in the St. Lawrence Valley: 1–5 June 2006, St. Lawrence County; and 7–8 June 2006, Franklin County. We conducted 2 surveys in the Adirondack Mountains: 13–14 June 2006, St. Lawrence and Franklin counties; and 21–27 June 2006, Essex County. We conducted 2 surveys in the Champlain Valley: 12–13 July 2006, Essex and Clinton counties; and 14–15 June 2007, Warren, Essex, and Washington counties. We conducted 2 surveys in the Great Lakes Plain: 26–27 July 2006, Jefferson and Oswego counties; and 25–26 June 2007, Wayne County. We conducted one survey in the Tug Hill Region: 5 June 2007, Lewis and Oneida counties.

### Additional Methodological Details

We verified that data distributions were normally distributed and homoscedastic before applying parametric statistical tests, and we applied data transformations if warranted; otherwise, we used nonparametric statistical tests. For nonparametric statistical tests, we corrected for ties. We arcsine square-root transformed all proportions before parametric statistical analysis; we ln-transformed AADT. We report standard deviations when variation around the mean is of inherent interest, otherwise we report standard errors. We report one-tailed $P$ values when there was an a priori directional hypothesis to a confirmatory test.

The NYSDEC provided permits for collecting herpetofauna (New York State Fish and Wildlife License 291). The

**Table 1.** Logistic regression models predicting presence or absence of herpetofauna road mortality at 100-m transect points that we sampled along rural highways in northeastern New York State, USA, during July 2002.

| Scale[a] | Model[b] | Log-likelihood | $K$[c] | AIC$_c$[c] | ΔAIC[c] | $w_i$[c] |
|---|---|---|---|---|---|---|
| All scales, without wetland configuration | | | | | | |
| 100 | Wet+res+comm | −62.109 | 4 | 132.503 | 0.000 | 0.309 |
| 50 | Wet | −64.386 | 2 | 132.856 | 0.353 | 0.259 |
| 100 | Wet | −64.414 | 2 | 132.913 | 0.410 | 0.252 |
| 50 | Wet+res+comm | −62.740 | 4 | 133.766 | 1.264 | 0.164 |
| 100 | Saturated | −61.398 | 8 | 139.855 | 7.353 | 0.008 |
| 50 | Saturated | −61.813 | 8 | 140.684 | 8.181 | 0.005 |
| 500 | Wet+res+comm | −67.809 | 4 | 143.903 | 11.400 | 0.001 |
| | Wet | −70.071 | 2 | 144.226 | 11.724 | 0.001 |
| 1,000 | Wet+res+comm | −68.970 | 4 | 146.226 | 13.724 | 0.000 |
| | Wet | −72.358 | 2 | 148.801 | 16.298 | 0.000 |
| | Intercept | −73.923 | 1 | 149.875 | 17.372 | 0.000 |
| 500 | Saturated | −67.488 | 8 | 152.034 | 19.532 | 0.000 |
| 1,000 | Saturated | −68.603 | 8 | 154.264 | 21.762 | 0.000 |
| 100-m scale only, including wetland configuration | | | | | | |
| 100 | Wet+res+comm+config | −61.027 | 5 | 132.486 | 0.000 | 0.116 |
| | Wet+res+comm | −62.109 | 4 | 132.503 | 0.017 | 0.115 |
| | Wet+config | −63.186 | 3 | 132.542 | 0.056 | 0.113 |
| | Res+comm+config | −62.160 | 4 | 132.605 | 0.119 | 0.109 |
| | Config | −64.354 | 2 | 132.793 | 0.307 | 0.100 |
| | Wet | −64.414 | 2 | 132.913 | 0.427 | 0.094 |
| | Res+config | −63.572 | 3 | 133.314 | 0.829 | 0.077 |
| | Wet+res+config | −62.515 | 4 | 133.316 | 0.830 | 0.077 |
| | Wet+comm | −63.662 | 3 | 133.494 | 1.008 | 0.070 |
| | Comm+config | −63.745 | 3 | 133.661 | 1.175 | 0.065 |
| | Wet+res | −63.774 | 3 | 133.719 | 1.233 | 0.063 |
| | Saturated | −60.498 | 9 | 140.330 | 7.844 | 0.002 |
| | Pasture | −71.259 | 2 | 146.602 | 14.116 | 0.000 |
| | Res | −72.387 | 2 | 148.858 | 16.372 | 0.000 |
| | Intercept | −73.923 | 1 | 149.875 | 17.389 | 0.000 |
| | AADT | −73.711 | 2 | 151.506 | 19.020 | 0.000 |
| | Comm | −73.719 | 2 | 151.522 | 19.036 | 0.000 |
| | Forest | −73.730 | 2 | 151.544 | 19.058 | 0.000 |
| | Rowcrop | −73.920 | 2 | 151.924 | 19.438 | 0.000 |

[a] Radial distance around point that land use was measured.

[b] Wet = wetland, res = residential, comm = commercial, config = configuration.

[c] $K$ = no. of parameters, AIC$_c$ = Akaike's Information Criterion, ΔAIC$_c$ = difference in AIC$_c$ from the best model, and $w_i$ = Akaike wt.

St. Lawrence County Highway Department and New York State Department of Transportation provided permits to work along the highways. The Clarkson University Institutional Animal Care and Use Committee approved the survey protocols (IRB155/IACUC 03-1).

## RESULTS

We detected road mortality at 21% of the 145 points surveyed (14.5 km of surveyed road); roadkill included 393 anurans (9 spp.: northern leopard frog [*Lithobates pipiens*], pickerel frog [*L. palustris*], bullfrog [*L. catesbeiana*], green frog [*L. clamitans*], mink frog [*L. septentrionalis*], wood frog [*L. sylvaticus*], gray treefrog [*Hyla versicolor*], spring peeper [*Pseudacris crucifer*], American toad [*Anaxyrus americanus*]), 6 turtles (2 spp.: painted turtle [*Chrysemys picta*], common snapping turtle [*Chelydra serpentina*]), 1 snake (common garter snake [*Thamnophis sirtalis*]), and 1 salamander (red-spotted newt [*Notophthalmus viridescens*]).

Models to predict the presence or absence of herpetofauna road mortality that included land cover quantified at a 100-m diameter around a point were best, but the 50-m-diameter scale was not much worse; both scales provided a better fit than the 2 larger scales (summed Akaike wt: 100 m = 0.569, 50 m = 0.429, 500 m = 0.002, 1,000 m = 0.000). Overall, a high proportional composition of wetlands around a point was the most important predictor of presence of reptile and amphibian road mortality (Tables 1, 2).

Survey points at causeways were more likely to have reptile or amphibian road-kill present (71.4% of the 14 causeway points) than points with one adjacent wetland (22.2% of 9 points) or points with no wetland present (14.8% of 122 points; $\chi^2$ contingency test, $\chi^2_2 = 24.6$, $P \leq 0.001$). Among the 29 points where amphibian mortality was present, the number of roadkill was higher at causeways than other points (causeway: $\bar{x} \pm \mathrm{SD} = 19.4 \pm 44.77$, other points: $0.9 \pm 4.59$; Mann–Whitney test, $U_2 = 37.7$, $P = 0.01$). All 3 points that had reptile mortality were located at causeways.

Models that included wetland configuration (causeway present or absent) as a predictor variable were better than those models that only included proportional composition of wetlands, but the 2 variables were about equally important. Proportional residential and commercial land uses were of

**Table 2.** Surrounding land use and traffic volume at 100-m transect points with herpetofauna road mortality ($n = 30$) and without herpetofauna road mortality ($n = 115$) along rural highways in northeastern New York State, USA, during July 2002.

| | Road mortality | | | |
|---|---|---|---|---|
| | Absent | | Present | |
| Predictor | $\bar{x}$ | SE | $\bar{x}$ | SE |
| Wetlands[a] | 2 | 0.6 | 17 | 5 |
| Forest[a] | 33 | 2.8 | 35 | 4.9 |
| Row crops[a] | 14 | 1.8 | 14 | 4 |
| Pasture[a] | 45 | 3 | 30 | 5.4 |
| Residential[a] | 5 | 1.6 | 1 | 1 |
| Commercial[a] | 2 | 0.5 | 3 | 1.7 |
| AADT[b] | 2,509 | 262.7 | 2734 | 498.4 |

[a] Percentage land use within 100 m of the survey point.

[b] Annual average daily traffic (vehicles/hr).

lesser importance (Table 1; summed Akaike wt: configuration = 0.658, wetland = 0.650, residential = 0.559, commercial = 0.478). Wetland configuration provided the best model among the set of models that were limited to one predictor variable (Table 1).

### Temporal Repeatability of Road Mortality Spatial Patterns

Road mortality recorded among the 200 surveyed points included 2,177 anurans, 34 turtles, and 3 snakes (40 sites each surveyed 5 times, cumulative 20-km road distance; species composition of the subsequent 4 surveys the same as the original survey with the addition of the eastern milk snake [*Lampropeltis triangulum*]). Using the summed count of total road-kill across all 5 surveys at each site, amphibian road mortality was positively associated with reptile mortality (Spearman rank correlation, $r_s = 0.49$, $P = 0.002$). Similarly, using the summed count of the number of surveys that had road mortality present, repeated presence of amphibian road mortality was positively associated with repeated presence of reptile mortality (Spearman rank correlation, $r_s = 0.34$, $P = 0.03$).

Mean abundance of road mortality (mean counts/point) varied markedly across survey periods for both amphibians (CV = 136%) and reptiles (CV = 66%). Nevertheless, the number of amphibians tallied at a point during a specified survey period was correlated with the overall trend, as estimated by the sum of the other 4 surveys ($r_s = 0.53 \pm 0.118$ [SD]; Fisher's combined test, $\chi^2_{10} = 78.7$, $P \leq 0.001$). The same was true for reptiles ($r_s = 0.20 \pm 0.123$; Fisher's combined test, $\chi^2_{10} = 23.9$, $P = 0.008$). Using all 10 pairwise Spearman rank correlations among the 5 surveys spaced 1 month to 49 months apart, we detected no indication of changes in inter-survey repeatability in ranked abundance among points that was associated with time between surveys (linear regression, amphibians: $F_{1,8} = 0.5$, $P = 0.5$; reptiles: $F_{1,8} = 0.1$, $P = 0.7$). The correlation between 40 points selected from the first (Jul 2002) survey and the sum of the other 4 surveys was moderate to high, indicating that the single-survey spatial patterns of road mortality analyzed in the previous results section provided an adequate snapshot of general long-term spatial patterns (amphibians: $r_s = 0.57$, $P \leq 0.001$; reptiles: $r_s = 0.30$, one-tailed $P = 0.03$).

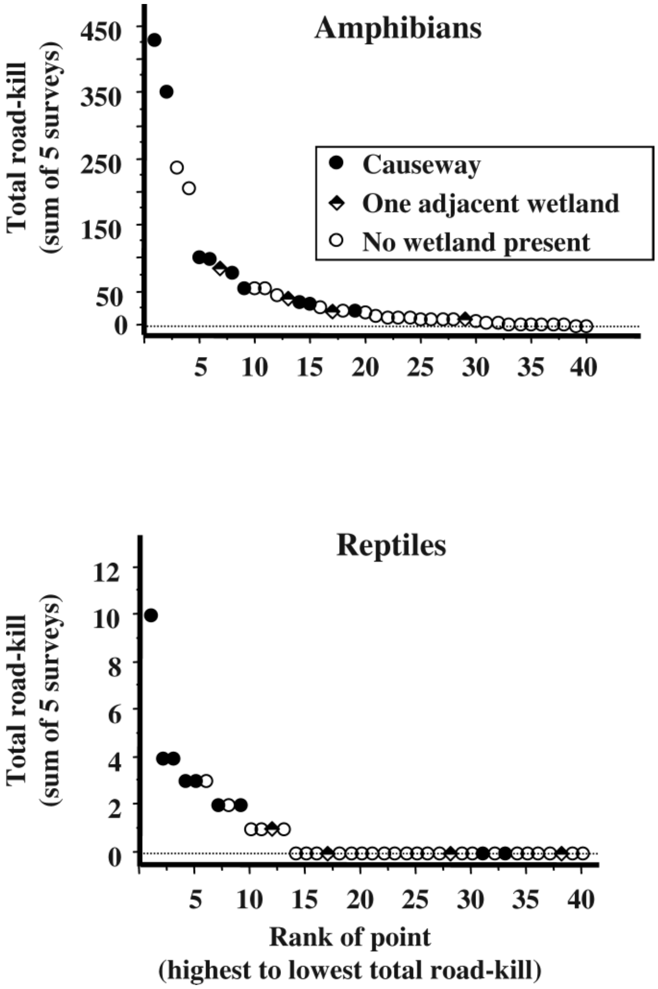

**Figure 1.** Summed counts of amphibian and reptile roadkill across repeated surveys at fixed survey points within the St. Lawrence River Valley of New York State, USA, ranked from highest to lowest summed road mortality. We surveyed the 40 points 5 times during 2002–2006.

The 40 survey sites included 9 causeways, 4 locations with one large (≥5.0 ha) adjacent wetland, and 27 locations with no large wetlands within a 100-m distance of the point. For amphibians, there were differences among the 3 categories of sites, with causeway sites being ranked higher in terms of total road mortality than the other two categories (Kruskal–Wallis test, $H_2 = 13.3$, $P \leq 0.001$). The same was true for reptile road mortality (Kruskal–Wallis test, $H_2 = 14.7$, $P \leq 0.001$). There were 4 times as many amphibians and 11 times as many reptiles at causeways as other points. Most road mortality was located at just a few of the surveyed points, and most of these hot spots were located at causeways (Fig. 1).

### Validating Causeways as Predictors of Hot Spots

Road mortality recorded among the 360 surveyed points (cumulative 36.0-km road distance) included 320 frogs, 50 turtles, 5 snakes, and 6 salamanders (species composition the same as the original survey with the addition of the wood

**Table 3.** Road mortality of herpetofauna along 100-m transects centered at causeways and random points within the highway network of 5 ecoregions of northeastern New York State, USA, which we sampled in June or July 2006–2007. Each survey period for a region is listed separately. $n = 20$ causeways and 20 random points per survey.

| | % of points withroad-kill | | | | | | | | Roadkill per point[a] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Reptile | | | | Amphibian | | | | Reptile | | | | Amphibian | | | |
| | Causeway | | Random | | Causeway | | Random | | Causeway | | Random | | Causeway | | Random | |
| **Region** | **%** | **SE** | **%** | **SE** | **%** | **SE** | **%** | **SE** | $\bar{x}$ | **SD (max.)** | $\bar{x}$ | **SD (max.)** | $\bar{x}$ | **SD (max.)** | $\bar{x}$ | **SD (max.)** |
| St. Lawrence Valley 1 | 20 | 8.9 | 0 | 0.0 | 35 | 10.7 | 0 | 0.0 | 1.5 | 0.58 (2) | NA[b] | | 2.7 | 1.70 (6) | NA | |
| St. Lawrence Valley 2 | 15 | 8.0 | 0 | 0.0 | 15 | 8.0 | 0 | 0.0 | 1.7 | 1.16 (3) | NA | | 2.0 | 1.00 (3) | NA | |
| Champlain Valley 1 | 10 | 6.7 | 5 | 4.8 | 45 | 11.1 | 5 | 4.9 | 1.0 | 0.00 (1) | 2.0 | 0.00 (2) | 2.2 | 2.59 (9) | 1.0 | 0.00 (1) |
| Champlain Valley 2 | 20 | 8.9 | 0 | 0.0 | 25 | 9.7 | 35 | 10.7 | 1.8 | 1.50 (4) | NA | | 2.4 | 3.13 (8) | 2.0 | 2.24 (7) |
| Adirondack Mountains 1 | 10 | 6.7 | 0 | 0.0 | 5 | 4.9 | 5 | 4.9 | 2.0 | 1.41 (3) | NA | | 1.0 | 0.00 (1) | 1.0 | 0.00 (1) |
| Adirondack Mountains 2 | 5 | 4.8 | 0 | 0.0 | 25 | 9.7 | 5 | 4.9 | 1.0 | 0.00 (1) | NA | | 1.6 | 0.55 (2) | 1.0 | 0.00 (1) |
| Tug Hill | 25 | 9.7 | 5 | 4.9 | 15 | 8.0 | 15 | 8.0 | 1.2 | 0.45 (2) | 1.0 | 0.00 (1) | 3.3 | 2.52 (6) | 4.0 | 0.00 (4) |
| Great Lakes Plain 1 | 25 | 9.7 | 15 | 8.0 | 80 | 8.9 | 15 | 8.0 | 1.8 | 1.10 (3) | NA | | 12.0 | 12.79 (45) | 1.7 | 0.82 (3) |
| Great Lakes Plain 2 | 30 | 10.2 | 0 | 0.0 | 30 | 10.2 | 30 | 10.2 | 1.5 | 1.22 (4) | 1.7 | 0.67 (3) | 2.5 | 1.726 (5) | 1.3 | 0.58 (2) |

[a] Only includes points where road mortality was detected.

[b] NA = not applicable, because no points had roadkill.

turtle (*Glyptemys insculpta* and Blanding's turtle [*Emydoidea blandingii*]). Causeway points during the 9 surveys across the 5 regions were more likely than random points to have amphibian road mortality present (Table 3; nominal logistic model, point [causeway or random] $\chi^2{}_1 = 17.5$, $P \leq 0.001$; point × survey $\chi^2{}_8 = 19.8$, $P = 0.01$). Reptile mortality was also more likely to be present at causeway than random points (Table 3; point $\chi^2{}_1 = 27.0$, $P \leq 0.001$; point × survey $\chi^2{}_8 = 7.8$, $P = 0.5$). The effect of the point × survey interaction for amphibians may be due to temporal or regional spatial variation in the extent to which causeways differ from random points in the density of roadkill; our schedule of surveys made it impossible to disentangle these nonexclusive possibilities.

For amphibian road mortality, 72 ± 7.7% (SE) of the points that had road mortality present were causeways (random expectation = 50%), and 78 ± 7.9% of the total roadkill tally was located at causeways. For reptile road mortality, 92 ± 4.4% of the points that had road mortality present were causeways, and 90 ± 5.5% of the total roadkill tally was located at causeways. Thus, causeway points were 3 times more likely than random points to have amphibian and 12 times more likely to have reptile mortality present, and causeways had a 4 times higher number of amphibian roadkill and 9 times higher reptile roadkill than did random points.

The highest point tally among the 40 points of each survey accounted for 34 ± 3.7% of amphibian and 51 ± 8.2% of reptile roadkill; the top 5 points accounted for 85 ± 4.1% of amphibians and 95 ± 3.4% of reptiles. Including only points that had amphibian roadkill present and only surveys where ≥1 causeway and one random point had roadkill present, there was a nonsignificant trend for the mean number of animals tallied to be higher at causeways than random points across surveys (Table 3; Wilcoxon signed rank test, one-tailed $P = 0.06$, $n = 7$), and the maximum number of animals tallied was higher at causeways (Table 3; Wilcoxon signed rank test, one-tailed $P = 0.01$, $n = 7$). We could not perform the same analyses for reptiles, because we so rarely detected reptile road mortality at random points during surveys (Table 3). Number of amphibians and reptiles at a point was positively associated (Spearman rank correlation, $r_s = 0.23$, $P \leq 0.001$).

When surveying, we did not detect the expected wetlands at 2% of the causeways points. At 3% of random points, we observed substantive wetlands on both sides of the road (an apparent causeway configuration) during the survey. Reanalysis using reclassified points based on ground-truthing did not qualitatively alter the results but did slightly increase the magnitude of the differences between causeways and random locations.

At 38% of random points, we noted permanent surface water or wetland indicator plants (e.g., *Typha*) in the vicinity. We recorded reptile road mortality at 13% of random points where we noted water versus 0% of points where we noted no water or wetland plants (Fisher's exact test, $P \leq 0.001$). We recorded amphibian road mortality at a higher percentage of random points where we had noted water or wetland plants than not (21% vs. 13%), but the difference was not statistically significant (Fisher's exact test, $P = 0.2$).

## DISCUSSION

We conclude that both amphibian and reptile road mortality are spatially clustered in northeastern New York State, and road-kill hot spots of the 2 taxa overlap. One survey provides a valid snapshot of spatial patterns of road mortality, and spatial patterns remain stable across time. Road-kill hot spots of reptiles and amphibians are associated with sites that have wetlands within 100 m of the road. Configuration of wetlands within 100 m of the road is a valid indicator of reptile and amphibian road mortality hot spots; roadkill is more likely to be present, and present in higher numbers, at causeways than at points with wetlands limited to one side of a road.

It is not surprising that reptile and amphibian road-kill hot spots are associated with wetlands. In northeastern New York, most species of each taxon are found within the vicinity of wetlands at least part of the year (Gibbs et al. 2007). In our study, the predominant amphibian species was the northern leopard frog, an abundant anuran that migrates from wetlands to upland areas to forage; the highest amphibian tallies coincided with the migration of metamorph leopard frogs out of natal wetlands in July. Leopard frogs, due to their migratory patterns, seem to be at higher risk of road mortality than are more sedentary anurans (Ashley and Robinson 1996, Pope et al. 2000, Carr and Fahrig 2001). The common snapping turtle and painted turtle, which were the most abundant road-kill reptiles in our study, move from wetlands to roads for nesting, resulting in female-biased road mortality (Steen and Gibbs 2004, Steen et al. 2006). Painted turtles are also known to regularly move overland between nearby wetlands (Bowne et al. 2006) and thus may be at elevated risk of mortality where roads bisect these wetland networks (Marchand and Litvaitis 2004).

The one component of the herpetofauna of northeastern New York that is missing from our survey data is vernal-pool breeding amphibians, composed of the blue-spotted salamander (*Ambystoma laterale*), spotted salamander (*A. maculatum*), and wood frog. These animals migrate from upland forest habitat to breeding pools during a brief period in early spring and can suffer high road mortality during these migrations (Gibbs and Shriver 2005, Compton et al. 2007). The timing of our surveys was inappropriate for these animals, and we caution that the spatial patterns of road mortality we reported are not necessarily applicable to vernal-pool breeding amphibians.

The timing of our surveys corresponded to a peak period of mortality of turtles and frogs in early summer. The timing was inappropriate for a second peak in early autumn, which corresponds with migration back to hibernation sites (see Langen et al. 2007, fig. 2). The few causeway sites that we monitored throughout the year seem to be consistently higher in road mortality than nearby sites outside of the causeway zone (T. A. Langen, Clarkson University, unpublished data), so we believe that causeways are always a valid predictor of high herpetofauna road mortality (exclusive of vernal pool species), but a fall season survey is needed to test this claim.

Factors that influence whether a location is a herpetofauna hot spot are likely to include species composition and population density in the vicinity of a road segment (Carr and Fahrig 2001, Hels and Buchwald 2001), road design (DeMaynadier and Hunter 2000, Shine et al. 2004), composition and configuration of wetlands and other habitat bordering the road (Findlay et al. 2001, Mazerolle and Desrochers 2005), volume and timing of traffic (Fahrig et al. 1995, Mazerolle 2004), behavior of animals upon approaching the road (Gibbs 1998, Shine et al. 2004, Andrews and Gibbons 2005), their behavior upon entering onto the road surface (Mazerolle 2004, Andrews and Gibbons 2005), and behavior of drivers encountering animals in the roadway (Langley et al. 1989, Ashley et al. 2007). A nontrivial result of our research is that causeway wetland configuration, and not simply wetland presence, is most highly associated with roadkill of reptiles and amphibians, which suggests that directed movements between wetlands, rather than simple random dispersal movements out of wetlands, may be an important cause of road crossing by the wetland-associated reptiles and amphibians in our region.

We identify 2 next-steps in developing the use of causeways as accurate predictors of reptile and amphibian road-kill hot spots. First, during our validation surveys, we had survey points at which the expected wetland was absent and others at which wetlands were unexpectedly present. There is a need to evaluate the error at locating causeways caused by inaccurate maps and (possibly) technician error and implement measures to increase accuracy at locating causeways. Initially, we evaluated 3 data maps that indicated regional wetlands (NYSDEC RFW map, the USGS NLCD map, and the United States Fish and Wildlife Service National Wetlands Inventory map) and available digital aerial orthoimages of survey sites (images dated 1994–1998, 1-m resolution). We found that although the maps indicated a generally similar configuration of wetlands, there was appreciable variation among them, doubtless because of differences in methodology used to create the maps (and hence map resolution), map age, and the original intended uses of the maps that determined what wetlands were included. Aerial images generally corresponded to the maps, but there were also some unexpected inconsistencies. There are likely to have been changes in wetland patterns within our surveyed regions between the time that the maps and aerial images were produced and the survey periods, due to widespread farm abandonment, numerous wetland reconstruction projects associated with the United States Department of Agriculture Wetland Reserve Program, an increasing beaver population, and some residential development (St. Lawrence County Agricultural and Farmland Protection Board 2001).

We detected significant variation in the density of roadkill among causeways. A second needed next-step is a structured comparison of causeways to determine what features result in a high frequency of road crossing by reptiles and amphibians. The design and age of the road; traffic patterns; composition, size, and orientation of component wetlands; presence or absence of culverts, bridges, or other potential passageways; and land cover or land use around the road and wetlands are all factors that may determine which causeways are most prone to elevated herpetofauna roadkill. Of particular conservation interest would be an evaluation of causeways made up of small wetlands, which may be below the regulatory threshold (e.g. $\leq$5.0 ha in NY), yet may nevertheless be important for maintaining populations of reptiles and amphibians (Gibbs 1993, Semlitsch and Bodie 1998).

Throughout the rural northeastern United States and southeastern Canada, the herpetofauna community and landscape are similar to the regions of northeastern New

York State that we surveyed. Thus, it is likely that causeways are important hot spots of herpetofauna road mortality over a large geographic region (e.g., Ashley and Robinson 1996). In warmer and in drier regions of North America, which have a greater diversity of reptiles and amphibians and more species that are not wetland-associated, it seems reasonable to suppose that herpetofauna road mortality would be less localized than we found and that other land cover or road features would be associated with road mortality hot spots. However, it is also plausible that presence of a causeway remains a valid predictor of elevated reptile and amphibian road mortality. In Florida, for example, the best-documented hot spots of herpetofauna road mortality are located at causeways (Bernardino and Dalrymple 1992, Smith and Dodd 2003, Aresco 2005*a*). We believe that it will be worthwhile to replicate our study in geographic regions very different from the northeastern United States, both to evaluate the general utility of our procedure for identifying valid predictors of road mortality hot spots and to assess whether causeways are associated with herpetofauna road mortality over a larger geographic scale and range of ecological conditions.

At present, mitigation projects aimed at reducing herpetofauna road mortality are implemented at a small number of high-profile sites in response to pressure of local interest groups; it is likely that most sites for effective mitigation are missed by this ad hoc approach (Evink 2002, Spellerberg 2002). Reptile and amphibian populations often have characteristics of either a metapopulation or one population in which individuals move among multiple, spatially separated patches; in either case movement between patches often requires crossing roads (Marsh and Trenham 2000, Semlitsch 2000, Joyal et al. 2001, Gibbons 2003, Roe and Georges 2007). Unless mitigation technologies and best-practices for reducing herpetofauna road mortality and maintaining connectivity are implemented systemically throughout a highway network, some species are likely to decline in landscapes that contain extensive road grids (Gibbs and Shriver 2002, 2005; Roe et al. 2006; Compton et al. 2007).

There is currently much research on the design and effectiveness of mitigation techniques to avoid road mortality of reptiles and amphibians, including use of barriers (walls and fences), underground passageways (culverts, bridges, and specially designed tunnels), and mechanisms to alter driver behavior (warning signs, speed limits, road closures; e.g., Langton 1989, Jackson and Griffin 2000, Bank et al. 2002, Evink 2002, Dodd et al. 2004). This research is essential, but mitigation efforts need to be focused at the sites where the need is greatest if an effective regional conservation strategy is to be implemented.

We identify 3 steps to developing an accurate and practical methodology for locating the sites that should be priorities for mitigation within extensive road networks or for locating sites to avoid when planning new roads. First, accurate data on spatial patterns of reptile and amphibian road mortality are necessary, which requires valid survey methodologies that are accurate and efficient at detecting spatial patterns of roadkill in lengthy road networks (Langen et al. 2007; see also Kline and Swann 1998, Steen and Smith 2006, Andrews et al. 2007), particularly because herpetofauna roadkill are not likely to be noted by conservation and law enforcement personnel or the public with the same care as ungulate and large carnivore mortality. The second step is to determine what features of the landscape, road, or local traffic patterns correlate with hot spots of reptile and amphibian mortality. The best potential predictors based on accuracy of prediction and ease of use should then be validated using various road networks imbedded in different landscapes. Useful predictors, from a management perspective, must be easily generated from existing geographical data, such as wetland and hydrology maps, land cover and land use data, and traffic surveys. The final step is to create an easy-to-use protocol by which road agency personnel and environmental managers can use the predictors to survey potential hot spots of road mortality throughout the road network for which they are responsible and prioritize these sites in terms of the need for mitigation. We are optimistic that this can be done wherever road mortality of amphibians and reptiles are a concern. Prioritized mitigation programs to reduce road mortality and increase connectivity should result in more economical and effective conservation of reptiles and amphibians in roaded landscapes and improved safety for motorists.

## MANAGEMENT IMPLICATIONS

Road mortality of reptiles and amphibians is highly clustered, and despite high temporal variation in roadkill, spatial patterns of herpetofauna road mortality can be detected even with one survey per site so long as all sites are surveyed within a short period and the conditions are suitable for terrestrial activity by these animals. Priority locations for survey of reptile and amphibian road mortality and mitigation planning should include causeways, because these are sites where roadkill is clustered for these taxa. Causeways can be located using GIS coverages such as regulatory wetland maps or high-resolution land cover data sets. By identifying valid predictors of hot spots of road mortality such as causeways, environmental and road managers can increase efficiency and accuracy at locating road mortality hot spots when planning new roads or surveying and planning mitigation along extensive existing road networks

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