Estimate of the Area Affected Ecologically by the Road System in the United States

RICHARD T. T. FORMAN
Harvard University, Graduate School of Design, Cambridge, MA 02138, U.S.A.

Abstract: *In view of an extensive road system, abundant and rapidly growing vehicular traffic, and a scattered literature indicating that some ecological effects of roads extend outward for >100 m, it seems likely that the cumulative ecological effect of the road system in the United States is considerable. Two recent studies in The Netherlands and Massachusetts (U.S.A.) evaluated several ecological effects of roads, including traffic noise effects, and provide quantitative evidence for a definable "road-effect zone." Based on the approximate width of this asymmetric convoluted zone, I estimate that about one-fifth of the U.S. land area is directly affected ecologically by the system of public roads. I identify a series of assumptions and variables suggesting that over time this preliminary estimate is more likely to rise than drop. Several transportation planning and policy recommendations, ranging from perforating the road barrier for wildlife crossings to closing certain roads, offer promise for reducing this enormous ecological effect.*

Estimación del Area Ecológicamente Afectada por el Sistema Carretero de los Estados Unidos

Resumen: *En vista de un sistema carretero extensivo, un abundante y creciente tráfico vehicular y una literatura dispersa indicando que algunos efectos ecológicos de las carreteras se extienden más allá de 100 m, parece probable que los efectos ecológicos acumulativos del sistema carretero en los Estados Unidos es considerable. Dos estudios recientes en los Países Bajos y Massachusetts (USA) evaluaron diversos efectos ecológicos de las carreteras, incluyendo efectos del ruido del tráfico y proporcionan evidencia cuantitativa para una definible "zona de efecto carretero". En base a la amplitud aproximada de esta zona conpleja y asimétrica, estimé que alrededor de una auinta parte del área terrestre de los Estados Unidos es directamente afectada ecológicamente por el sistema de carreteras públicas. Identifiqué series de conjeturas y variables que surgieren que a lo largo del tiempo esta estimación preliminar es mas probable que incremente a que disminuya. Diversos planes de transportación y recomendaciones políticas, que van desde perforar la barrera carretera para propiciar el cruce de vida silvestre hasta el cierre de ciertas carreteras ofrecen la promesa de reducir este efecto carretero.*

Introduction

The 6.2 million-km system of public roads in the United States, used by 200 million vehicles, permeates and links essentially every local area (National Research Council 1997). These roads and roadsides cover about 1% of the land, equivalent in area to Austria or South Carolina. A suite of ecological effects of roads involving species, soil, and water has been identified, with effects varying in distance outward from meters to kilometers (Ellenberg et al. 1991; Forman 1995). The outer limits of these significant ecological effects along a road thus describe a "road-effect zone" (Fig. 1; Forman et al. 1997; Forman & Deblinger 1998, 1999).

A limited amount of evidence for the width of the road-effect zone is available from Europe and North America. Therefore, my objective was to estimate the total area or proportion of the United States ecologically affected by the road system.

A road system of course has both positive and negative ecological effects, and understanding these helps to identify solutions for transportation policy and planning. Transporting people and goods efficiently between points is a familiar advantage of roads to society. Less recognized is the resulting ecological protection of the

Paper submitted June 14, 1999; manuscript accepted July 10, 1999.

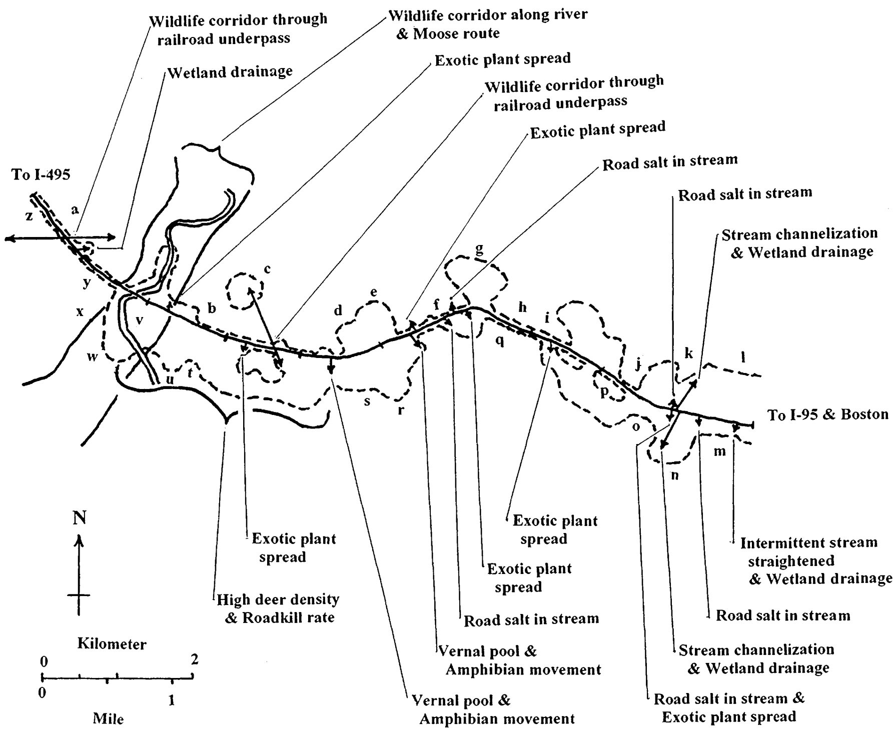

Figure 1. Road-effect zone along 10 km of a Massachusetts highway. Locations of key road effects are indicated by arrows. Dashed lines border areas where forest and grassland bird communities are estimated to be affected by traffic noise (effect-distance for most sensitive species is 680 m in forest and 810 m in grassland; M. Reijnen et al. 1995; R. Reijnen et al. 1995, 1996). Factors near the road that affect the width of a traffic-noise effect are indicated by letters: (a) built area, (b) built area, (c) downwind of (agricultural) grassland, (d) low area, (e) forest, (f) road embankment, (g) forest, (h) road embankment, (i) built area, (j) road embankment and built area, (k) hill, (l) forest, (m) built area, (n) forest, (o) low embankment by road, (p) built area, (q) road embankment, (r) forest, (s) small hill, (t) forest, (u) grassland, (v) river, (w) open wetland area, (x) golf course, (y) hill, and (z) built area. This section of Route 2, a four-lane divided highway west of Boston that supports 50,000 vehicles/day, begins 2 km west of Interstate Highway 95 and extends 10 km through Lincoln and Concord. Modified from a study of 25 km along Route 2 (Forman & Deblinger 1998, 1999).

surrounding matrix against disturbance by convoluted routes, "random searches," or off-road vehicles. Another example of an ecological benefit is the maintenance of native grassland plants and of nesting sites on roadsides in landscapes of intensive agriculture. In Australia a giant green nature reserve borders the road network in many agricultural landscapes (Forman & Alexander 1998). Nevertheless, most of the ecological effects of road systems are negative, and their cumulative effect covers an extensive area. Mitigation and transportation planning solutions for most of the ecological effects exist in scattered locations (Forman & Hersperger 1996; Canters 1997; Forman et al. 1997; Forman & Alexander 1998), but the widespread use of such solutions awaits recognition by the scientific community, highly visible pilot projects, and greater public understanding.

The road-effect zone is also promising as a basis for transportation planning. Landscape ecologists and scholars of related fields increasingly recognize ecological flows across the landscape as critical for long-term nature protection (Forman 1995, 1999; Harris et al. 1996). For example, groundwater, surface water, foragers, dispersers, migrants, pollinators, fire, heat energy, and sediments move across the heterogeneous landscape of patches, corridors, and matrix. These flows and movements create and maintain patterns from spatial to biological diversity. In contrast to this landscape-wide perspective, transportation engineers focus closely on the road or highway itself and the critical narrow band alongside. Road design and construction involve local factors, such as roadbed particle sizes, erosion, sediment flows, soil drainage, erosion, slopes, ditches, plantings, bridges, and guardrails, and are accomplished according to precise codes and practices. The spatial disconnect between these ecological and engineering perspectives is striking. The road-effect zone appears promising as a middle ground, the spatial perspective that provides both the ecological and engineering objectives of society.

The ecological factors determining the road-effect zone are related to species, soil, and water. Effects extend outward and can be linked directly to a specific road. I excluded from my analysis the indirect ecological effects of transportation, such as air pollutants in vehicle emissions that accumulate in the atmosphere and cause ecological effects often far from the source road (National Research Council 1997).

The total area of the road-effect zone for a nation was first estimated for The Netherlands by R. Reijnen et al. (1995) and was based on avian community composition in forest and agricultural grassland at varying distance from main roads. Evidence indicates that traffic noise is the major cause of the degradation of avian communities near busy roads (M. Reijnen et al. 1995; R. Reijnen et al. 1995, 1996). The average density of Dutch main roads (highways) is 0.3 km/km^2, compared with an average of 0.13 km/km^2 for main (state-maintained) roads in the United States and 1.2 km/km^2 for all U.S. public roads. Traffic volume on Dutch main roads apparently ranges from 10,000 to >100,000 vehicles per day, presumably a higher average than in the United States. In addition to more main roads and traffic, The Netherlands has proportionally more built area, more open land, and less forest than the United States. This means that on average traffic noise should affect a greater portion of The Netherlands. Secondary roads and roads in urban areas apparently were not included in the Dutch studies.

R. Reijnen et al. (1995) estimate that 10% of the land area of The Netherlands is significantly disturbed ecologically by traffic noise. This estimate is based on the average effect-distances—distance that a significant effect extends from a road—for all bird species combined. In contrast, based on the most sensitive bird species, which are of primary conservation importance, the authors estimate that >17% of the land is disturbed. Avian diversity is reduced and total bird density is one-third lower in the areas affected by roads and vehicles. These estimates are based on 1986 data, and, due to traffic increases, the figures are projected to be 15–20% higher in 1999. Therefore road-effect zones apparently cover at least 12–20% of The Netherlands.

A recent study measured and estimated nine ecological variables along a 25-km, divided four-lane highway in Massachusetts and incorporated the Dutch results in the analysis (Forman & Deblinger 1998, 1999). All effects believed to extend >100 m from the road were included in the study: wetland drainage, stream channelization, road salt in surface water bodies, planted roadside exotics invading forest, moose (*Alces alces*), deer (*Odocoileus virginiana*), forest birds, grassland birds, and vernal pool amphibians. The road-effect zone was then mapped (Fig. 1), which highlighted its (1) asymmetry (2) convoluted borders, and (3) occasional "fingers" protruding from a border. Some effects such as traffic noise appeared along much of the road length, whereas a few effects including stream channelization occurred only at points along the road. Asymmetry of the zone results from directional wind- and water-flow processes and from differences in topography, land use, and habitat suitability on opposite sides of the road. Thus the Massachusetts and Dutch studies provide the basis for a preliminary estimate of the total area ecologically affected by a road system.

Estimate for the United States

Assumptions

To make an estimate of the total ecological effect of the U.S. system of public roads, I made the following assumptions:

(1) Total area of United States is 9,372,610 km^2.

(2) Total road length includes 3,836,381 km of secondary roads in rural areas (county, town, township, federal [U.S. Forest Service, U.S. National Park Service, and reservations that are not part of the state or local highway systems], and other local public roads), 1,237,198 km of primary roads (under state control) in rural areas, 927,122 km of secondary roads in urban areas, and 178,394 km of primary roads in urban areas (Fig. 2a).

(3) All road length in rural areas and 25% of road length in urban areas are roughly estimated to be near natural ecosystems (for both primary and secondary roads). Natural ecosystems include agricultural land (which, for example, contains grassland birds of conservation interest) but exclude built areas (thus ignoring ecological effects there). Near natural ecosystems means adjoining or close enough to produce road effects.

(4) Traffic volume (24-hour total, Monday through Friday, half the vehicles going each direction, roughly estimated averages) for primary roads in rural areas (highways in towns, villages, and more remote areas) is 10,000 vehicles/day and in urban areas is 50,000 vehicles/day.

(5) Road-effect zones for primary roads (in both rural and urban areas) are calculated as two times the effect distances for the most sensitive bird species highlighted in the Dutch studies (R. Reijnen et al. 1995, 1996). The effect distance is 305 m for 10,000 vehicles/day in woodland, 365 m for 10,000 vehicles/day in grassland, and 810 m for 50,000 vehicles/day in natural ecosystems in urban areas (average of results for forest birds and grassland birds; Forman & Deblinger 1999).

(6) Road-effect zone for secondary roads is 200 m wide, a rough estimate for a highly variable zone. Lower traffic volume may be associated with localized short-distance effects, such as most roadkills or road dust and road salt effects on vegetation, whereas higher traffic volume produces long-distance effects, including blocking wildlife corridors and subdividing populations into smaller, less stable subpopulations.

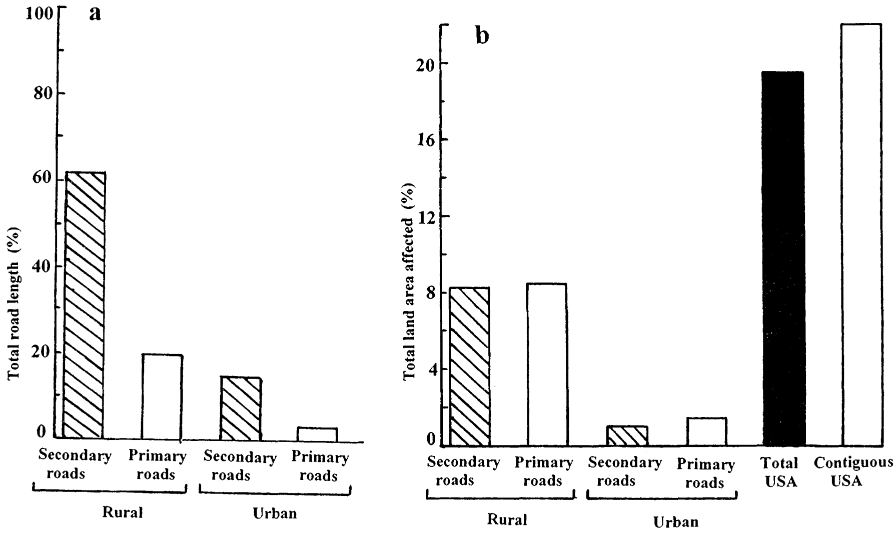

Figure 2. The (a) road length and (b) area affected ecologically by roads in the United States. Total road length in the United States is 6.2 million km (Federal Highway Administration terminology and data for 1985). Area ecologically affected is calculated based on estimates of road-effect zones in Massachusetts and The Netherlands and on other data.

Estimated Area

Calculations based on the preceding assumptions indicate that 19% of the total area of the United States is directly affected ecologically by roads and associated vehicular traffic (Fig. 2b). A breakdown of this total by road type and location shows that roads in rural areas have by far the greatest total ecological effect (16.7% vs. 2.5% in urban areas). Primary and secondary roads have the same total ecological effect (Fig. 2b), even though primary roads are only one-quarter of the total road-network length (Fig. 2a). Excluding Alaska (which has few roads in a large area) and Hawaii means that 22% of the contiguous United States is estimated to be ecologically altered by the road network (Fig. 2b).

Variables that Lower or Raise the Estimate

It is useful to identify key variables that would lower or raise these overall estimates. The following would be expected to lower the estimated area affected ecologically: (1) Eliminate overlapping road-effect areas in the vicinity of road intersections in rural areas and in high-road-density urban areas. (2) Ignore the most sensitive species and calculate the effect-distance of primary roads based on the density of all species combined (R. Reijnen et al. 1995, 1996; Forman & Deblinger 1999). (3) Calculate the effect-distance based only on variables whose effects generally extend meters to tens of meters outward, such as roadbed erosion and heavy-metal effects on populations (Forman & Alexander 1998). (4) Assume that primary roads in rural areas have an average traffic volume of <10,000 vehicles/day. For example, if traffic volume is 5000 vehicles/day, the effect-distance decreases somewhat; if traffic volume is <3000 vehicles/day, the effect-distance for avian communities may be less than that for several other road effects (van der Zande et al. 1980; M. Reijnen et al. 1995; R. Reijnen et al. 1996). (5) Reduce the road-effect zone width on secondary roads. If it were halved to 100 m, for example, the total affected area in the contiguous United States would be 18% instead of 22%. (6) Omit roads in agricultural and other human-modified open landscapes even though sensitive grassland birds are present.

In contrast, the following key variables would be expected to raise estimates of the total U.S. area ecologically affected: (1) Include the effects of cutting or blocking of major long-distance wildlife corridors. (2) Include the effects of subdividing previous large populations into smaller populations occupying isolated patches distant from the road in which the populations remain as less stable and more vulnerable to local extinction. (3) Add the effects of human access to remote areas (due to the presence of roads) where overhunting or varied human disturbances occur, sometimes affecting large areas. (4) Include areas by secondary roads subjected to certain long-distance effects, such as some stream and river channelization, sedimentation downstream of bridges, altered water tables, wetland drainage, and spread of planted roadside exotic species into nearby natural ecosystems. (5) Assume that traffic volume on secondary roads in rural or urban areas exceeds an average of 10,000 vehicles/day, so the road-effect zone based on the most sensitive bird species would be greater than the 200 m used in calculations. (6) Increase the road-effect zone for primary roads in rural grasslands by using the most sensitive species actually recorded in the Dutch studies (it was presumed to be an outlier and hence omitted from calculations), which would triple the width of the road-effect zone. (7) Use 1999 in lieu of 1985 transportation data (total road length has changed little; National Research Council 1997). With rapid urbanization, however, urban road length has significantly increased and rural road length decreased. Also, traffic volume has increased as people spend more time driving. Therefore in 1999 more road length has higher traffic volume than in 1985 and, consequently, greater ecological effect-distances would be used in the calculations. (8) Add the ecologically affected area by nonpublic roads, including logging areas on private timberland, farm and ranch roads, and driveways. (9) Include the effects of off-road vehicles.

Comparing the lists of factors that may decrease or increase the estimated ecological effect of roads suggests that one-fifth of the United States land area is a conservative estimate of ecological effects. It is more likely that future estimates based on additional data will rise rather than fall. Also, if the effects of vehicular air pollutants such as CO_2, O_3, and NO_X (National Research Council 1997) were added, the cumulative effect of the road system would be still greater.

Conclusion and Policy Implications

A significant portion of the ecological literature is doubtless based on studies within road-effect zones. In thinking about this literature and in designing research studies of the future, greater attention to the ecological effects of roads is warranted. Roads, and especially traffic, are increasing in the United States and worldwide. Clearly, the estimate of total area affected ecologically is a preliminary estimate. Better data sets and fuller analyses should lead to better estimates in the future.

My calculations suggest some policy approaches that could have a significant effect on reducing the huge area affected directly by roads and vehicles. The following five actions could make a difference. (1) Perforate the road as a barrier to animal movement by using tunnels, underpasses, overpasses, and other mitigation technology, thus reducing the effects of blocking wildlife corridors and of subdividing populations into smaller, less stable subpopulations. (2) Close, and where ecologically important, remove logging and other roads in remote areas to reduce the disturbance effects of human access. (3) Increase the use of soil berms, plantings, depressed roads, and other construction techniques to reduce the distance and area ecologically affected by traffic noise. (4) Concentrate traffic on primary roads, especially in rural landscapes, and minimize the conversion of secondary roads from light- to medium-traffic usage. (5) Reduce traffic noise by changing tire design, vehicle aerodynamics, road surface, proportion of truck traffic, and total amount of vehicle miles (kilometers) traveled. Such policy changes would reverberate through society, yet I suspect that the demand for appropriate solutions to the ecological road-system effects that permeate the land is closer than we think.

Acknowledgments

I am pleased to acknowledge colleagues on a National Research Council committee on the future of U.S. transportation in a sustainable environment, as well as R. Reijnen's studies, which initially stimulated my interest in this subject. I warmly thank S. R. Godwin and R. D. Deblinger for key insights.

Literature Cited

Canters, K., editor. 1997. Habitat fragmentation & infrastructure. Ministry of Transportation, Public Works and Water Management, Delft, The Netherlands.

Ellenberg, H., K. Muller, and T. Stottele. 1991. Strassen-Okologie. Pages 19-115 in Okologie und strasse. Broschurenreihe de Deutschen Strassenliga, Bonn, Germany.

Forman, R. T. T. 1995. Land mosaics: the ecology of landscapes and regions. Cambridge University Press, Cambridge, United Kingdom.

Forman, R. T. T. 1999. Horizontal processes, roads, suburbs, societal objectives, and landscape ecology. Pages 35-53 in Landscape ecological analysis: issues and applications. Springer-Verlag, New York.

Forman, R. T. T., and L. E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics **29**:207-231.

Forman, R. T. T., and R. D. Deblinger. 1998. The ecological road-effect zone for transportation planning, and a Massachusetts highway example. Pages 78-96 in G. L. Evink, P. Garrett, D. Zeigler, and J. Berry, editors. Proceedings of the international conference on wildlife ecology and transportation. Publication FL-ER-69-98. Florida Department of Transportation, Tallahassee.

Forman, R. T. T., and R. D. Deblinger. 1999. The ecological road-effect zone of a Massachusetts (USA) suburban highway. Conservation Biology **14**:36-46.

Forman, R. T. T., and A. M. Hersperger. 1996. Road ecology and road density in different landscapes, with international planning and mitigation solutions. Pages 1-22 in G. L. Evink, P. Garrett, D. Zeigler and J. Berry, editors. Trends in addressing transportation related wildlife mortality. Publication FL-ER-58-96. Florida Department of Transportation, Tallahassee.

Forman, R. T. T., D. S. Friedman, D. Fitzhenry, J. D. Martin, A. S. Chen, and L. E. Alexander. 1997. Ecological effects of roads: toward three summary indices and an overview for North America. Pages 40-54 in K. Canters, editor. Habitat fragmentation and infrastructure. Ministry of Transport, Public Works and Water Management, Delft, The Netherlands.

Harris, L. D., T. S. Hoctor, and S. E. Gergel. 1996. Landscape processes and their significance to biodiversity conservation. Pages 319-347 in O. Rhodes Jr., R. Chesser, and M. Smith, editors. Population dynamics in ecological space and time. University of Chicago Press, Chicago.

National Research Council. 1997. Toward a sustainable future: addressing the long-term effects of motor vehicle transportation on climate and ecology. National Academy Press, Washington, D.C.

Reijnen, M. J. S. M., G. Veenbaas, and R. P. B. Foppen. 1995. Predicting the effects of motorway traffic on breeding bird populations. Ministry of Transport and Public Works, Delft, The Netherlands.

Reijnen, R., R. Foppen, C. ter Braak, and J. Thissen. 1995. The effects of car traffic on breeding bird populations in woodland. III. Reduction of density in relation to the proximity of main roads. Journal of Applied Ecology **32**:187-202.

Reijnen, R., R. Foppen, and H. Meeuwsen. 1996. The effects of car traffic on the density of breeding birds in Dutch agricultural grasslands. Biological Conservation **75**:255-260.

van der Zande, A. N., W. J. ter Keurs, and W. J. van der Weijden. 1980. The impact of roads on the densities of four bird species in an open field habitat—evidence of a long distance effect. Biological Conservation **18**:299-321.