Title

Good and bad places for roads: effects of varying road and natural pattern on habitat loss, degradation, and fragmentation

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Good and Bad Places for Roads: Effects of Varying Road and Natural Pattern on Habitat Loss, Degradation, and Fragmentation

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Abstract: Improving ecological conditions around the road network is emerging as a significant objective of transportation, along with providing safe and efficient mobility. Reading landscape patterns is a key to success. The prime goal of this article is to identify ecologically appropriate and inappropriate locations for road construction, removal, and mitigation in the network. Other goals include understanding the effect of road location between two large natural patches, and progress in developing an ecologically optimum network form.

Simple spatial models are used with three independent variables: (1) road size or connection, (2) road location relative to natural patch or corridor, and (3) size/width of patch or corridor. Dependent variables are habitat loss, degradation, and fragmentation. Modeling results suggest that in a landscape of dispersed natural patches and corridors, by far the greatest road effect (ecological impact) results from a highway that bisects or highway network that subdivides a large natural patch.

Overall, effects are greatest where a road crosses or is alongside large patches and wide corridors. For both types, the least effect is where a small road is alongside the margin. Road effects are relatively low around narrow corridors and lowest around small patches. Model results indicate that the probability of species crossing between two large natural patches is lowest where a highway slices across near the midpoint.

A highway network has a greater effect on habitat conditions in a natural landscape than in an agricultural or suburban landscape. Habitat degradation appears to have a greater ecological effect than does habitat loss or fragmentation in the landscape. An ecologically optimum road network contains: a few large roadless areas; a few busy roads rather than many lightly used roads; and perforated roads (for species movement) between the large roadless areas.

In conclusion, a simple patch-corridor analysis of a landscape points to clear solutions for locating road construction, removal, and mitigation to maximize ecological benefits. The two overarching principles are minimizing roads in and around large natural patches and maximizing effective habitat connectivity between the large natural patches.

Introduction

Transportation aims to provide safe and efficient mobility. However, a consequence of society's road network is a huge detrimental effect on nature's patterns and processes across the landscape. Roads tend to be relatively straight lines, traditionally curved to avoid hazards and natural topographic features. However, the widespread abundance of natural patches and corridors in the landscape (fig. 1) now, with rigorously documented ecological characteristics, offers a promising new handle for evaluating and minimizing road impacts. With road construction, removal, or mitigation at strategic points, this cumulative impact can be dramatically and efficiently reduced. In this article, I identify spatial patterns, strategic points, and working principles for transportation and society.

Road ecology is the lens for solution. In the 1980s major thinking, initial publications, and government action began in Europe (Ellenberg et al. 1981, Langton 1989, Aanen et al. 1991). In the U.S.A., the conceptual framework for road ecology as a field was first developed in half a chapter of the book, *Toward a Sustainable Future* (National Research Council 1997). Beginning in about 1995, a remarkable energizing interaction sprang up among transportation specialists, ecologists, wildlife biologists, and other scientists in both Europe and North America (Evink et al. 1996, van Bohemen 1996, Forman and Hersperger 1996, Friedman 1997, National Research Council 1997). The widely dispersed lines of thought and evidence quickly coalesced, and were developed into a meaningful body of theories and principles, together with a richness of published studies and useable applications, in the book *Road Ecology* (Forman et al. 2003).

Today, major new highway systems are under construction in China, India, and Eastern Europe. Meanwhile, in the U.S.A., road construction is limited (<1% annual increase) and focused on local development areas near cities (Transportation Research Board 2002). Road ecologists now can often estimate the ecological effect of a small road or a multilane highway for a specific site or local habitat. Similarly, an effect can be estimated, albeit in more general terms, for the broader landscape (fig. 1). Both effects are important for planning and policy.

Habitat loss, degradation, and fragmentation are frequently related to roads and are particularly useful and convenient measures of road effects at both site and landscape scales. Indeed these habitat conditions are readily related to spatial arrangement (effectively distance between road and habitat), to road size (partially a function of width but mainly related to traffic volume), and to size and shape of natural habitat.

Figure 1. Landscape composed of large and small wooded patches, wide and narrow corridors, and an open background matrix. Note wide corridor (right center) providing connectivity for wildlife movement between large patches and small road (upper right) providing human access into large wooded area, with consequent habitat degradation effects. Road ecologists and transportation planners should be able to read these fundamental landscape patterns and pinpoint the ecologically best and worst locations for a busy highway or a small road. Southeastern Australia. R. Forman photo.

The approach for considering natural habitat is a key to this analysis and the consequent pinpointing of good and bad road locations. First, landscape-ecology analyses have highlighted the value of the patch-corridor-matrix model (Forman and Godron 1981, Forman 1995, Bennett 1999). In effect, all points in virtually any landscape are either in a patch, a corridor, or the background matrix, each with simple spatial attributes, such as large-to-small, wide-to-narrow, and perforated-to-continuous (fig. 1). Extensive literature and evidence relates a range of ecological characteristics to these spatial patterns (Forman 1995, Meffe et al. 1997, Bennett 1999, Liu and Taylor 2002, Gutzwiller 2002). Therefore, the arrangement of roads relative to these basic spatial patterns provides considerable insight into landscapes worldwide. Reading this landscape pattern is a key to identifying the best and worst locations for large and small roads.

Thus the broad objectives of this article are to understand the relationship between road network and natural habitat and to provide planning guidelines for the network to improve ecological patterns and processes in the landscape noticeably. The specific questions are:

1. Where in a landscape of natural patches and corridors is the ecologically best place for constructing, removing, or mitigating a road?
2. What is the ecological effect of location of a road slicing between two natural patches?
3. What is the relative importance of road-caused habitat loss, degradation, and fragmentation in different landscapes?
4. What is the ecologically optimum road network form and what are the determinant principles?

Methods and Assumptions

The basic approach is simple spatial modeling using two to four "representative" conditions for each of the variables considered. Independent variables are: (1) road size or connection; (2) road location relative to patch or corridor; and (3) size/width of patch or corridor. The varied patch/corridor forms are also weighted for their relative ecological importance. The dependent variables are habitat loss, degradation, and fragmentation, plus their sum. Independent variables and their combinations are compared to provide understanding of relative, rather than absolute, effects, such as from highest to lowest (ecologically worst to best).

In selecting the conditions or values of each variable, I chose to scale variables to one another relative to expected effects, rather than attempting to use numbers from specific studies which only indirectly relate to the questions here. This procedure helps provide broad applicability to diverse landscapes. However, the conditions chosen inevitably evolve out of my experience observing certain landscapes worldwide, as well as our studies of roads, traffic, birds, and other ecological characteristics in the northeastern USA (Forman and Deblinger 2000, Forman et al. 2002, 2003).

For the roads variable, the following are used for comparison: busy highway, small road, and highway network. I think of "busy highway" as referring to a two-lane or multilane road with more than about 15,000 vehicles per commuter day (Forman et al. 2002), although various factors could lower or raise that traffic level. A small road might have perhaps <8000 veh./day, or even <400 veh./day (AASHTO 2001). In one analysis here, low traffic refers to a small road, and high traffic to a busy highway. A network of small roads is not included in the analysis, though its important role in facilitating human access and disturbance in large natural patches and natural landscapes (fig. 1) is indirectly recognized in the habitat-degradation assay.

For the natural patterns variable, the following are used for comparison: large patch, small patch, wide corridor, and narrow corridor. Natural (ecological) pattern refers to one of these spatial elements in a landscape, which may have formed by natural processes alone or in combination with human activities. A large natural patch is considered to contain many uncommon or rare species in the patch interior, whereas a small patch contains few or none. A wide natural corridor provides for frequent movement along its length of some patch-interior species, whereas a narrow corridor provides for infrequent or rare movement along its length of patch-interior species. For weighting the relative overall importance of the natural patterns, the analysis presents ecological characteristics widely documented in the literature as correlating with the natural patterns are presented in the analysis.

Roads are placed through the middle of a natural pattern or alongside it. In one analysis, roads are placed at different locations across a wide natural corridor connecting two large patches.

In scaling road and natural patterns, the busy highway produces a degradation zone on each side that extends an arbitrary 25 percent of the width of the large natural patch and 75 percent of the wide corridor. A small road has a degradation zone on each side that extends to 10 percent of the width of a large patch, 50 percent of a small patch, and 100 percent of a narrow corridor.

Road effects are measured by habitat loss, degradation, and fragmentation (Forman et al. 2003, van Bohemen 2005). These are separately estimated in the analyses and then summed for an overall effect. Roadkill is not added as an assay since it is strongly related to the natural spatial patterns and the three major habitat variables included. Also, roadkill's main ecological effect seems limited to certain types of species (Mech et al. 1988, Langton 1989, Fahrig et al. 1995, Iuell et al. 2003) . Habitat loss refers to the area of natural habitat removed for a road and its roadsides. Habitat degradation refers to the zone alongside a road where natural habitat is significantly altered. Dozens of factors can degrade adjacent habitat (Forman et al. 2003). However, the two primary causes of a wide zone of habitat degradation here are considered to be traffic noise plus disturbance due to human access.

The third component, habitat fragmentation, at a landscape scale is mainly due to wide swaths of agricultural, residential, and other land, not roads. In this study, fragmentation refers to the functional separation or barrier to natural flows and movements between natural areas on opposite sides of a road. The clearest case is when a busy highway as a partial barrier bisects a large natural patch, corridor, or a natural landscape. However, where the busy highway bisects farmland or residential land that in turn separates two natural patches, the highway further reduces flows and movements between the patches. In this case, habitat fragmentation is increased due to degradation (e.g., by traffic noise) of the agricultural or residential land by the highway.

In one analysis, the overall effect of the road network is compared for agricultural and suburban landscapes versus natural landscapes. Agricultural and suburban landscapes with scattered natural patches and corridors illustrate the patterns of the preceding analyses. In contrast, the natural landscape (such as forest or desert) has a matrix of natural or semi-natural ecosystems where road effects may be quite different.

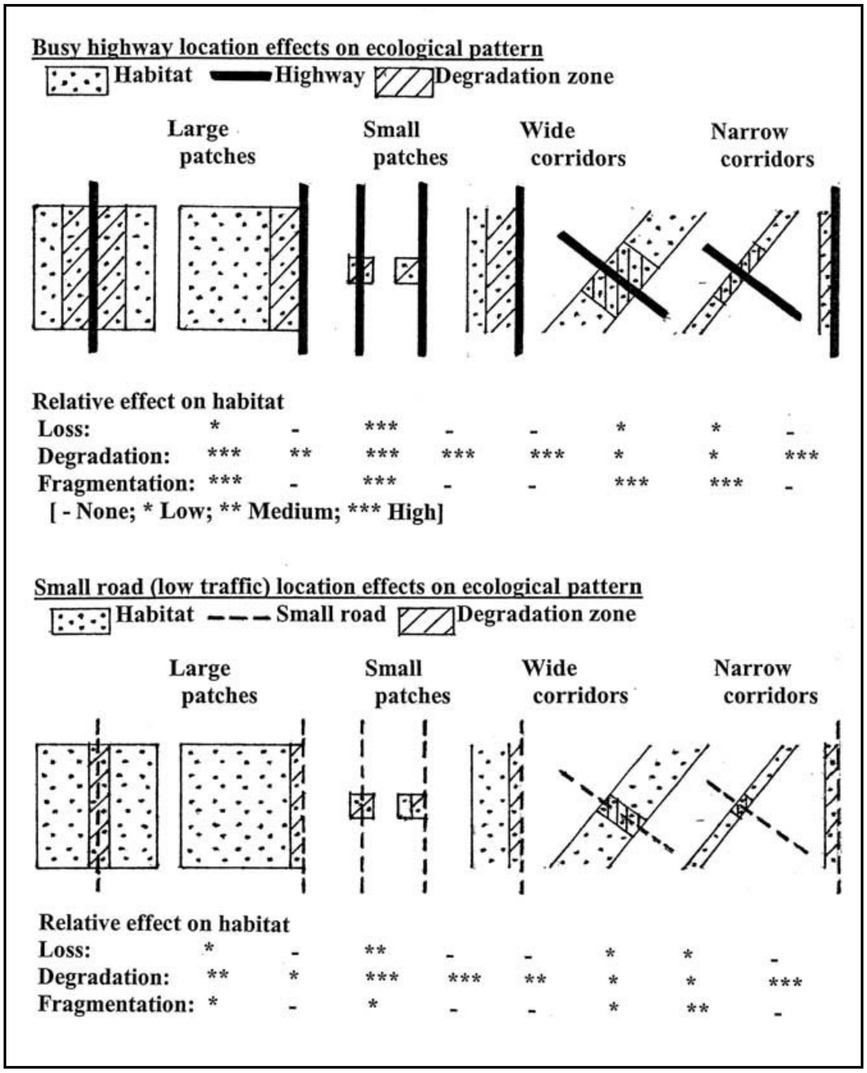

Figure 2. Location of busy highway and small road relative to natural patches and corridors in the landscape. The relative effect of a road on habitat loss, degradation, and fragmentation of a particular patch or corridor is indicated by the number of asterisks in eight columns (corresponding to the preceding eight diagrams) and is estimated based on the spatial arrangements portrayed.

The final question on network form highlights the importance of getting beyond the useful but preliminary concept of road density to understand the ecologically optimal form of a road network for a landscape or region. This is an evolving search, with one additional key principle and pattern added to the two principles previously identified for an optimum network (Forman 2004).

Results and Discussion

Roads relative to natural patches and corridors in the landscape

When a busy highway is placed across the center of a large natural patch, relatively little of the overall habitat is directly lost (fig. 2, top). However, the spatial model suggests that a considerable amount of habitat is degraded and that the large patch is noticeably fragmented. The relative effect of placing the highway alongside a large patch is much lower, since there is no habitat loss or fragmentation and the area of habitat degradation is less. Placing the busy highway across or alongside a small natural patch (fig. 2, top) has a major impact on that patch. Overall, a highway across or alongside a wide or narrow corridor produces an intermediate effect on habitat conditions (fig. 2, top). Alongside the corridor, the highway produces severe habitat degradation, whereas crossing the corridor the highway has a major habitat-fragmentation effect.

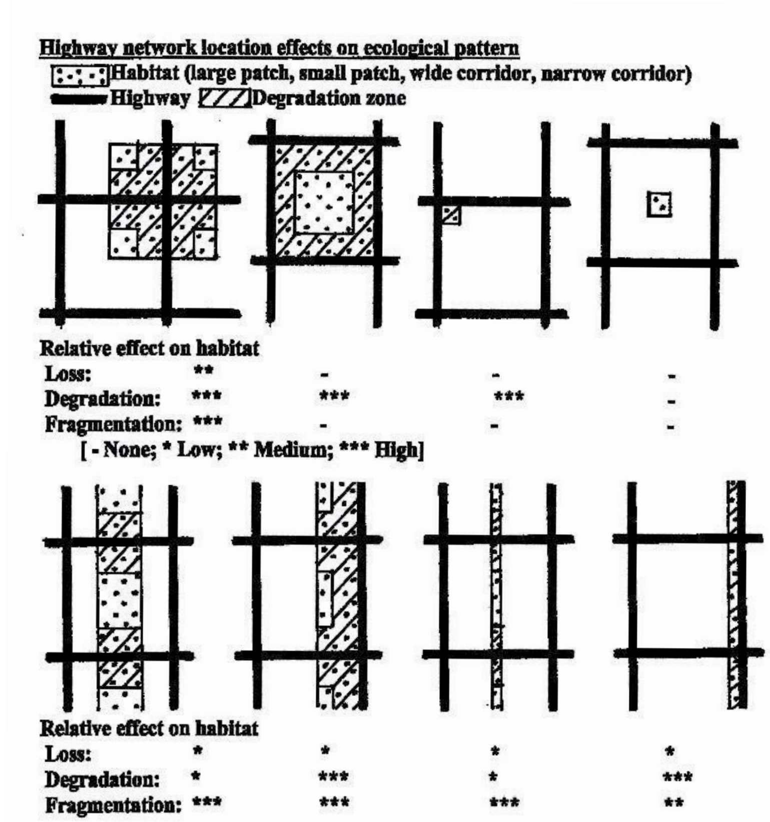

Figure 3. Location of highway network relative to natural patches and corridors in the landscape.

Spatial patterns of nature with associated ecological characteristics

***1. Large patches*: Clean aquifer/groundwater protection**
Connected headwater stream network
MVP of patch-interior species
Large-home-range species
Facilitate semi-natural disturbance regime
Microhabitat proximities for multihabitat species

***2. High corridor connectivity*: Continuous habitat**
Facilitates dispersal of species
Recolonization of large patches
Gene flow reduces inbreeding depression

***3. Small patches*: Stepping stones for dispersal & recolonization**
Protect isolated microhabitats & species
High species densities
Escape cover

***4. High boundary length*: Enhances game species in edge**

***5. Low boundary length*: Reduces edge and often exotic species**

***6. Low corridor connectivity*: May reduce spread of exotics & pests**
Decreases gene flow

Figure 4. Major ecological characteristics associated with natural patches and corridors in the landscape. Ecological characteristics are synthesized from two decades of extensive literature.

A small road placed across or alongside natural patches and corridors produces a similar, though less-severe overall effect on habitat conditions (fig. 2, bottom). The number of "effect asterisks" provides a summary effect of habitat conditions for each of the 16 patch/corridor and road combinations (fig. 2, top and bottom). Thus, in this preliminary analysis, the most severe effect (nine asterisks) is where a highway crosses a small natural patch and the least effect (one asterisk) occurs where a small road passes alongside a large patch.

The relative effects of a highway network on the natural patches and corridors highlight additional patterns. The greatest effect illustrated (eight asterisks) is where the network crosses and subdivides a large patch into sections (fig. 3). The effect is also severe (seven asterisks) where the network passes both along and across a wide corridor. The least effect is in the case of a small patch in the center of a network enclosure. These preliminary summary effects refer to the specific ecological spatial patterns, such as a large patch or narrow corridor.

However, since the ecological spatial patterns are clearly of different overall ecological value, the results of figures 2 and 3 are now weighted for ecological value (fig. 4). Large natural patches are by far the most important (Forman 1995, Meffe et al. 1997, Gutzwiller 2002). Wide corridors are considered to provide better connectivity for species movement than narrow corridors (Forman 1995, Bennett 1999, Gutzwiller 2002). Small patches provide less benefit (Forman 1995, Meffe et al. 1997, Gutzwiller 2002). Boundary length conditions and low corridor connectivity are considered to be of still lower ecological priority in the landscape (Forman 1995) and are not included in the analysis.

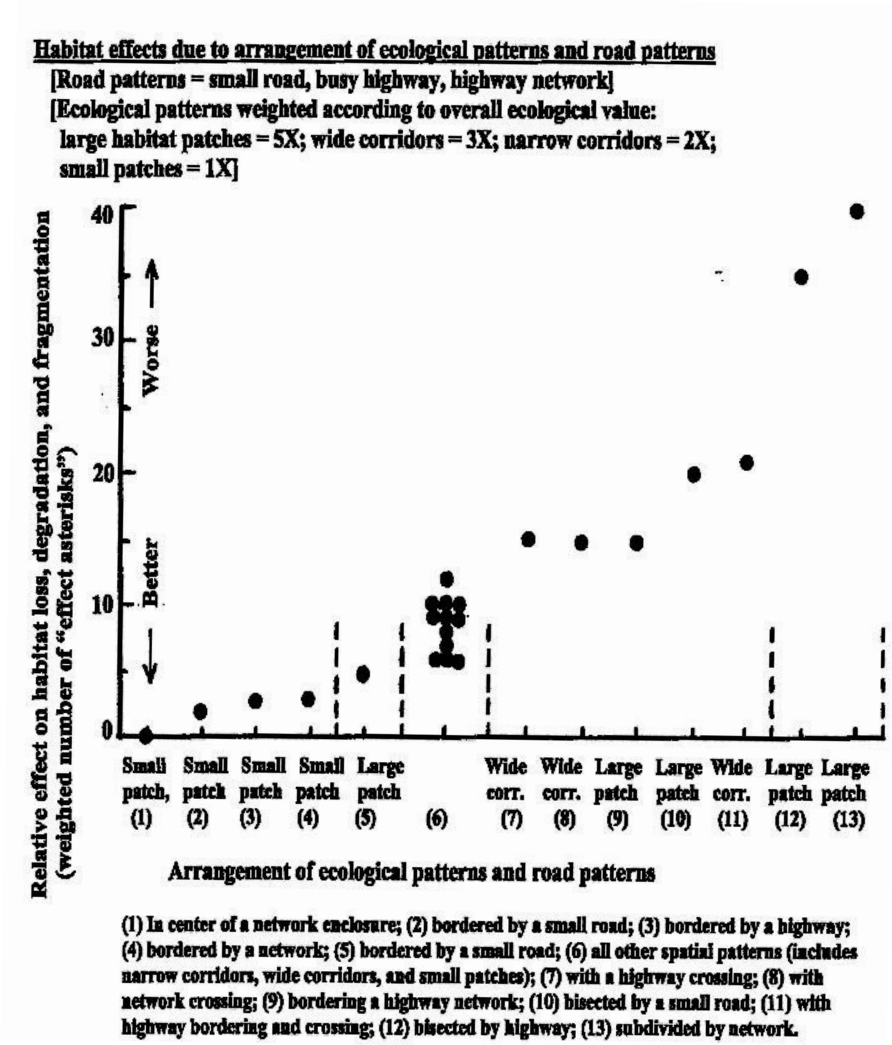

Figure 5. Summary of habitat effects according to arrangements of ecological and road patterns. The ecological effect of 24 arrangements of roads relative to patches/corridors in a landscape were separately estimated [– None; * Low; ** Medium; *** High] for habitat loss, degradation, and fragmentation (figs. 2 and 3). Natural patches/corridors were then weighted for overall ecological values (see top of figure). Weights were multiplied times the number of asterisks to give a weighted number of "effect asterisks" for each of the 24 spatial arrangements.

Thus the ecological spatial patterns are arbitrarily weighted for ecological value as follows: large natural patches = 5X; wide corridors = 3X; narrow corridors = 2X; and small patches = 1X (for large patches 10 to 20X is more realistic, but using the conservative 5X gives about the same comparative results). The weights are then multiplied times the summary number of habitat "effect asterisks" for each of the 24 patch/corridor and road/network conditions in figures 2 and 3. In this way, the relative effect of arranging road and ecological patterns on habitat loss, degradation, and fragmentation in the landscape can be estimated.

Based on the spatial model, by far the greatest effects are where the highway or network bisects or subdivides a large natural patch (fig. 5). Relatively large effects occur for most other road arrangements involving large patches, as well as wide corridors. The effect of roads crossing or along narrow corridors is relatively low. The least ecological effect is where roads are placed on or next to small natural patches (fig. 5). Although small patches may be severely affected, normally they are of relatively little ecological value.

A closer look at road arrangements relative to the important large natural patches and wide corridors is instructive. The highway or network that bisects or subdivides a large patch (fig. 6, top) effectively destroys many of the large-natural-patch values (fig. 4). Serious degradation of habitat conditions occurs in five of the large-patch and wide-corridor arrangements (fig. 6, top and bottom): a highway network surrounding a large patch; a small road bisecting a large patch; and three cases where a highway crosses a wide corridor. In another five ("try to avoid") arrangements, habitat effects are noticeable, though less severe. Unlike these important large-patch and wide-corridor cases, the overall effects of placing roads across or alongside small patches and narrow corridors are relatively minor (fig. 5).

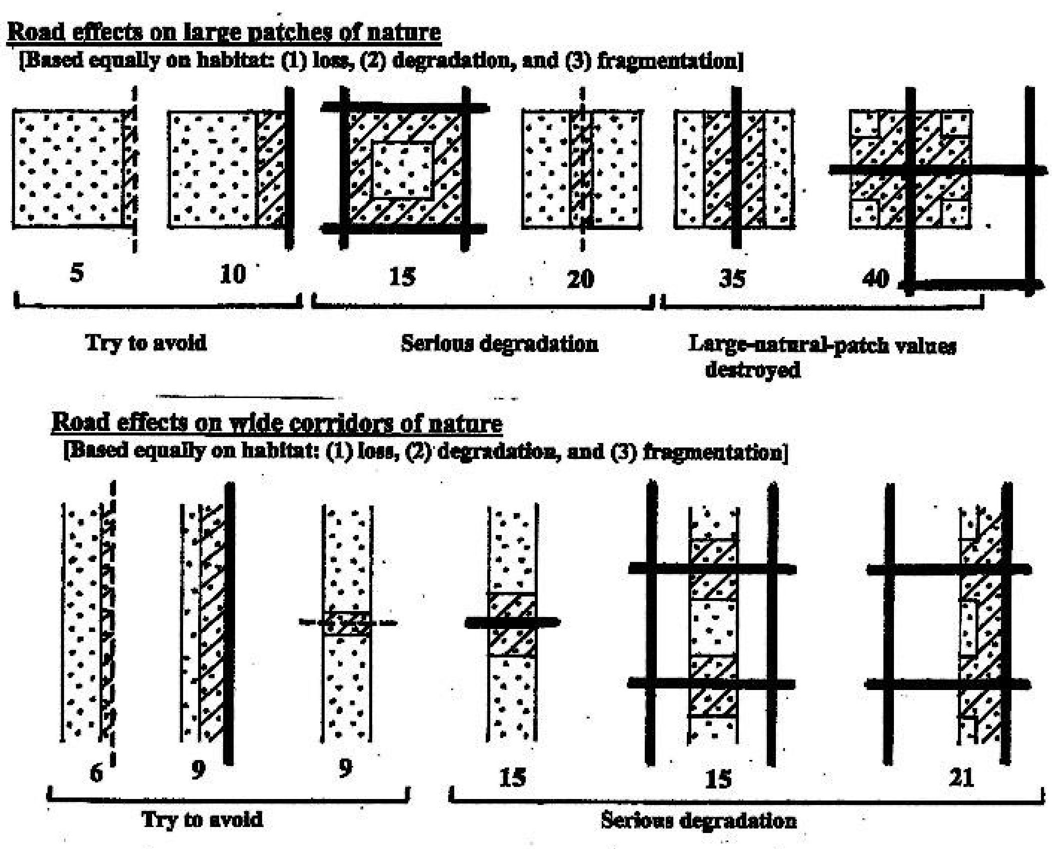

Figure 6. Busy highways and small roads relative to large patches and wide corridors, which are the most important natural patterns. Numbers refer to the weighted number of "effect asterisks" (fig. 5), and represent most of the arrangements of roads and patches/corridors with the greatest ecological effect.

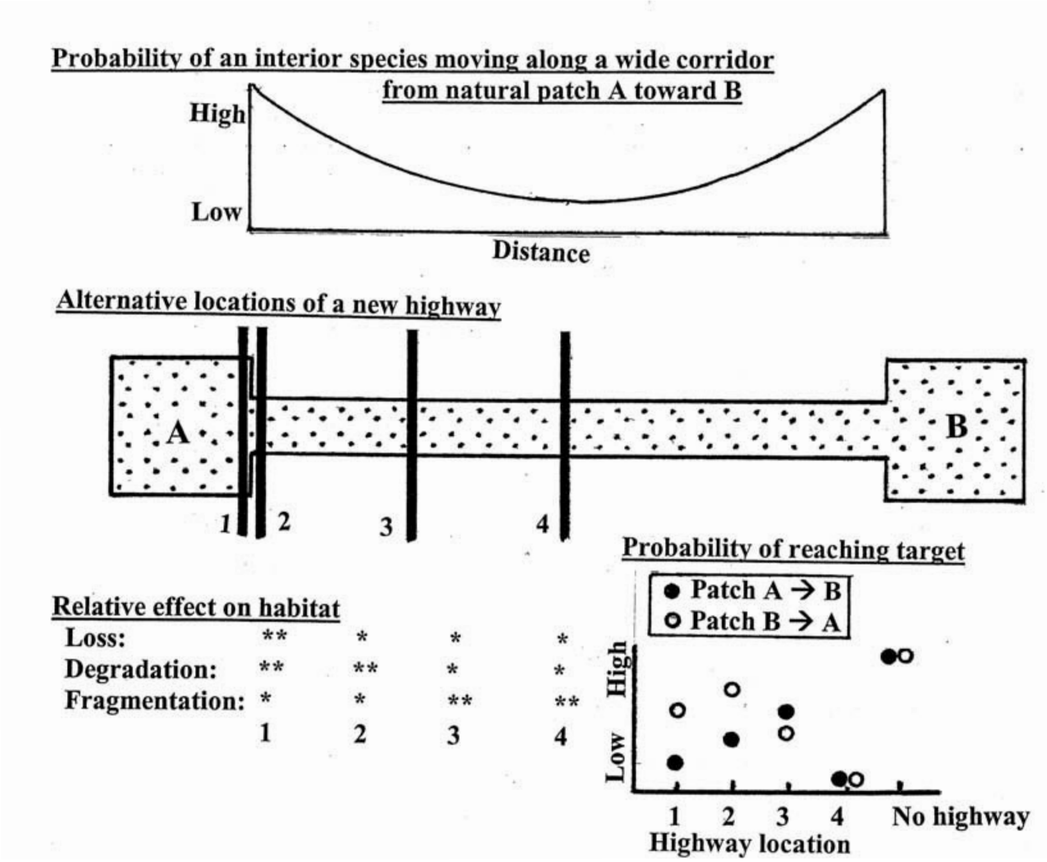

Figure 7. Location of a highway and the probability an interior species will successfully cross between large natural patches. Large habitat patches A and B are connected by a wide natural corridor. Curve at top is hypothesized based on scattered literature evidence. Numbers indicate alternative highway locations. Graph in lower right is estimated based on curve at top plus habitat effects in lower left.

Road location between two natural patches

Consider an interior species moving along a wide corridor from large natural patch A toward large patch B (fig. 7, top). Initially, there is a high probability of moving forward, but with distance the probability drops as animals progressively become further from their preferred habitat in A (Wegner and Merriam 1979, Forman and Baudry 1984, Bennett 1999). Perhaps after passing the midpoint, the animals see or realize that they are now closer to the target patch B, so the probability of onward movement increases.

Now consider the effect on species movement of adding a busy highway that slices between the large natural patches (fig. 7, middle). The highway could be in the edge of patch A, alongside the patch, cross at about 25 percent of the distance along the corridor, or at the midpoint between the patches. The loss, degradation, and fragmentation measures suggest that road locations would all have about the same summary effect on habitat conditions of the large patches and wide corridor (fig. 7, lower left).

However, combining this effect on habitat conditions with the forward-movement probability (fig. 7, top) provides insight into the probability of an interior species reaching a target patch (fig. 7, lower right). The spatial model indicates that a highway at the midpoint between patches results in the lowest chance of species reaching a target patch. For species movement from patch A to B, the greatest success rate is where a highway is a quarter of the length along the corridor. However, for an animal moving in the opposite direction from patch B to A, the highest probability of successful movement appears to be with a highway alongside patch A. Locating a highway at the 25 percent point between patches may be the best ecological solution.

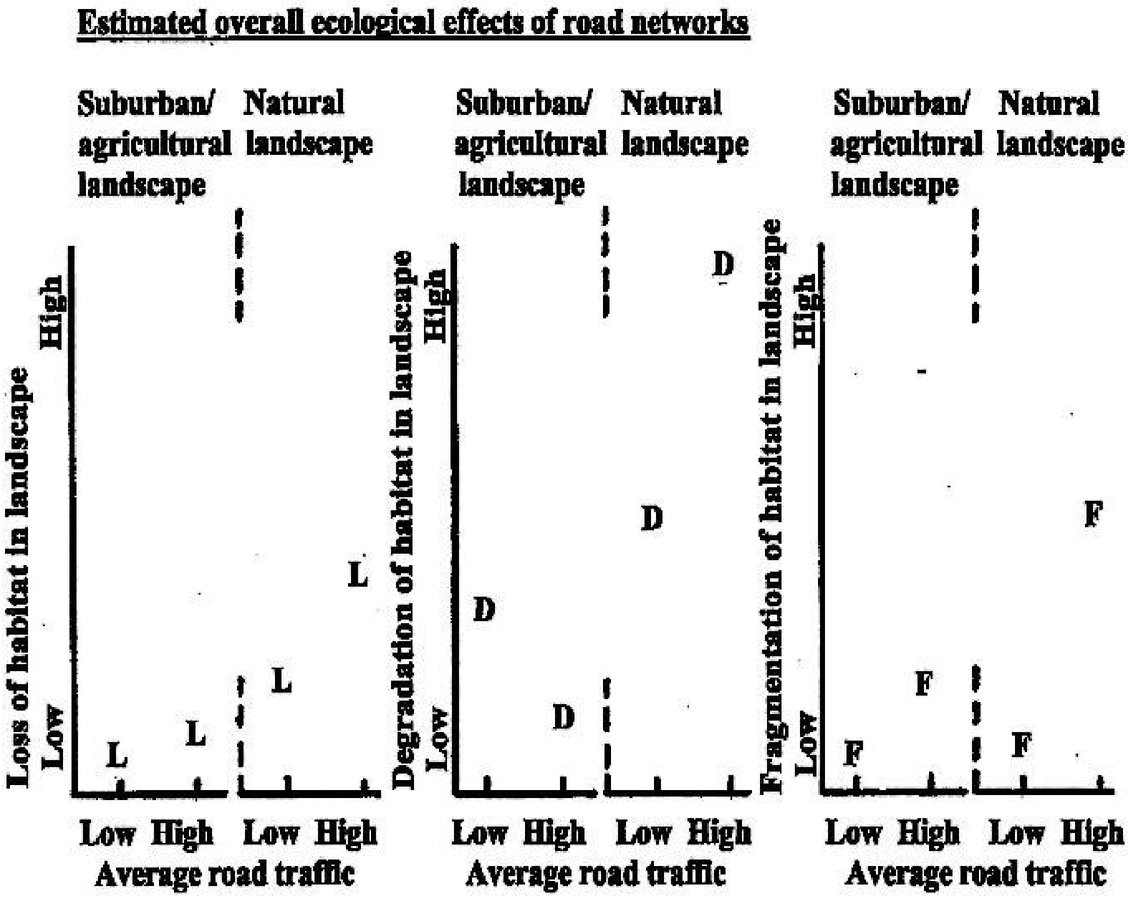

Figure 8. Estimated overall effects of road networks on habitat loss, degradation, and fragmentation in different landscapes. Suburban and agricultural landscapes typically have dispersed natural patches and corridors present, whereas natural landscapes are mainly covered with natural or semi-natural habitat.

Road-caused habitat change in different landscapes

The patches-and-corridors analysis (figs. 2 to 6) is particularly applicable in suburban and agricultural landscapes, where land-use change has resulted in natural patches and corridors in a matrix less suitable for patch-interior species of conservation interest. In contrast, a natural landscape contains a matrix of natural or semi-natural habitat in which a road network typically has been built. Thus the relative effect of habitat loss, degradation, and fragmentation due to the road network can be expected to differ in different landscape types. A network of low-traffic small roads probably also differs in effect compared to a network of high-traffic busy highways.

The three graphs in figure 8, which are based largely on qualitative estimates, suggest that the overall ecological effect of a road network is greater in a natural landscape than in a suburban or an agricultural landscape. The graphs also indicate that habitat degradation has the greatest effect in different landscapes and that (relatively) habitat loss is a minor effect. High-traffic roads have a greater effect than low-traffic ones.

One exception appears in the suburban or agricultural landscape, where low-traffic roads are the primary access for human-caused habitat degradation in the interior of large natural patches (fig. 8). The habitat fragmentation effect of high-traffic roads in suburban and agricultural landscapes is due in part to the degradation effects alongside highways passing through built land or farmland.

Ecologically optimum network form

Road density has often been used as an overall measure of the effect of a road network on wildlife populations (Mech et al. 1988, Mladenoff et al. 1995, Forman and Hersperger 1996, Clevenger et al. 1997). It has also been related to hydrologic conditions, stream density, fire ignition and control, human access effects, and indeed overall ecological conditions in a landscape (Jones 2000, Jaeger 2000, Forman et al. 2003). Yet, although easily measured and communicated, road density is a relatively crude or general measure.

Network form appears to be a much more sensitive measure of ecological conditions, but as yet is little studied (Reed et al. 1996, Tinker et al. 1998, Forman and Mellinger 1999, Jaeger 2002, Forman et al. 2003).

Two principles and consequent patterns have been identified in the search for an optimum ecological network form (Forman 2004): (1) maintain a few large roadless natural areas and (2) concentrate the bulk of the traffic onto a small number of large roads. Large natural areas sustain clean water-supply aquifers, interior species of conservation interest, and much more (fig. 4). One large highway creates less area impacted by noise, emissions, and habitat loss than do two small highways (Ellenberg et al. 1981, Forman et al. 2003).

A third principle is proposed here: perforate or mitigate roads that separate the large natural areas. The goal is to maintain effective species connections among the areas and thus sustain viable populations of key interior species.

The three principles are listed in order of overall significance. More are likely to be identified or developed. Many network forms can accomplish these three principles. One promising network form is presented with the principles illustrated (fig. 9).

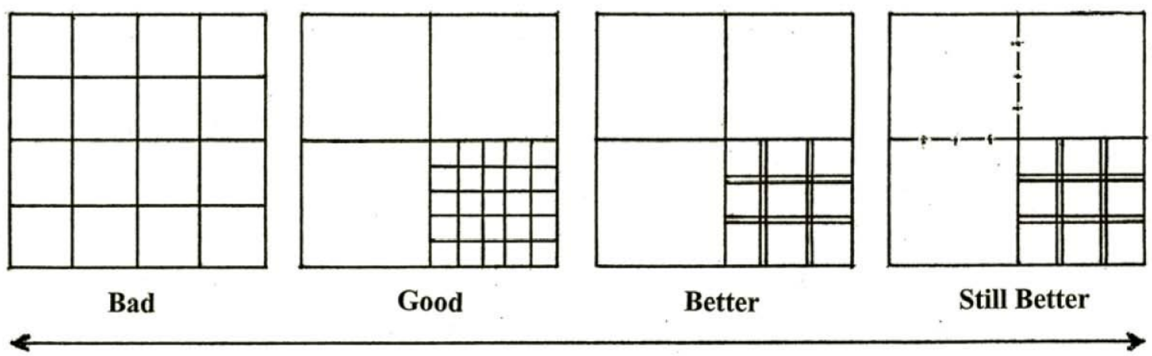

Figure 9. Road network form, illustrating three principles underlying an ecologically optimum network. The principles: (1) maintain a few large roadless natural areas; (2) concentrate the bulk of the traffic onto a small number of large roads; and (3) perforate or mitigate roads that separate the large natural areas. See Forman (2004); also Forman (1995), Forman et al. (2003).

Conclusion

The patch-corridor-matrix model of landscapes provides a convenient, effective, and readily understood handle for prioritizing locations for road construction, removal, and mitigation to provide ecological benefits. The results of the patch-corridor and road analyses presented point to two overarching principles for planning and policy: (A) minimize roads in and around large natural patches or areas and (B) maximize effective habitat connectivity between the large natural patches. Both are accomplished in strategic locations with new-road avoidance and/or road-segment removals (Kruse 1998, Iuell et al. 2003, Forman et al. 2003, Switalski et al. 2004). The second technique can also include road mitigation and compensation, including wildlife underpasses and overpasses, roadbed and road surface modifications, woody vegetation in roadsides, and other approaches (Friedman 1997, Iuell et al. 2003, Forman et al. 2003, Forman 2005, Clevenger and Waltho 2005, van Bohemen 2005). Several more-detailed guidelines are also pinpointed in this article.

I sense that these are sufficiently important and straight-forward (indeed compelling) to become guidelines in road construction, road removal, and road mitigation. Implementation will visibly accomplish a vision: a sustainable emerald network of large natural patches connected by major wildlife, water, and walker corridors across landscapes, effectively meshed with a road network providing safe and efficient mobility for people and goods.

Major societal objectives will be combined on the land. The conservation community should become strong supporters and collaborators with transportation.

Biographical Sketch: Richard T. T. Forman is the PAES Professor of Landscape Ecology at Harvard University, where he teaches ecological courses in the Graduate School of Design and in Harvard College. His research and writing include landscape ecology, road ecology, land-use planning and nature conservation, and urban-region ecology. He received a B.S. (Haverford College), Ph.D. (University of Pennsylvania), honorary Doctor of Humane Letters (Miami University), and honorary Doctor of Science (Florida International University). He has taught at Rutgers University and the University of Wisconsin, served as president or vice-president of three professional societies, and received awards and honors in Australia, China, Colombia, Czech Republic, England, France, Italy and the U.S.A. He has authored numerous articles and his books include *Landscape Ecology* (1986), the award-winning *Land Mosaics* (1995), *Landscape Ecology Principles in Landscape Architecture and Land-use Planning* (1996), *Road Ecology* (2003), and *Mosaico territorial para la region metropolitana de Barcelona* (*Land Mosaic for the Greater Barcelona Region: Planning a Future*) (2004).

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