SPATIAL MODELS AS AN EMERGING FOUNDATION OF ROAD SYSTEM ECOLOGY AND A HANDLE FOR TRANSPORTATION PLANNING AND POLICY

Richard T. T. Forman
Harvard University
Graduate School of Design
Cambridge, MA 02138, USA

Abstract

As transportation-related environmental issues and associated public concern rapidly grow, fortuitously, the science of road system ecology also emerges. To link broad ecological flows across the landscape with key engineering dimensions immediately around a road, simple spatial models appear particularly promising. Eight useful examples gleaned from road systems worldwide, as well as from theory, are introduced: (a) *perforated roadbeds* help overcome the barrier effect by enhancing the crossing of animals and water; (b) *giant green network* provides connectivity and biological diversity in intensive agriculture landscapes; (c) *shrinking populations model* links habitat loss, roadkill, edge effect, disturbance, and the subdividing barrier effect of a road; (d) *road-effect zone* delineates the ecologically minimum area for transportation planning; (e) *network-and-node theory* combines routes and destinations, both varying in size, traditionally for transport economics; (f) *road-density/mesh-size* links diverse effects from mammals to fire and water; (g) *network variability* highlights ways of gaining benefits from nature=s variability; and (h) *ecological road fitting* pinpoints the arrangement of interactions with streams, slopes, corridors, patches and species. Such spatial models represent a growing foundation of theory for road system ecology. They also offer visual and conceptual simplicity to stimulate communication among ecologists (including wildlife experts), engineers, economists, the public, and policy makers. Better road systems, which provide for safe and efficient human mobility and also provide effectively for ecological flows and biodiversity, should emerge.

Introduction

Providing safe and efficient human mobility and attempting to minimize environmental impacts are key goals of transportation. In consequence, human mobility has flourished while nature has suffered. In many nations, and in state after state of the USA, the public increasingly expresses interest or concern about the environmental impacts of road systems (including traffic on them). Headlines relating roads to wildlife, biodiversity, water and soil are growing.

Coinciding with this burgeoning public interest is an emerging and distinctive science of road system ecology. It has important roots in water flow, erosion and sediment transport, wildlife movement and roadkill, mitigation for wildlife, roadside vegetation, aquatic system impacts, air pollution, and more (Ellenberg et al. 1981, Bennett 1991, Aanen et al. 1991, Natuur over Wegen 1995, Evink et al. 1996, 1998, Canters 1997, National Research Council 1997, Forman and Alexander 1998). With the advent of landscape ecology (Saunders and Hobbs 1991, Forman 1995, Bennett 1999), road ecology is coalescing for good reason. Roads slice through and affect a series of local ecosystems or land uses in a landscape. Indeed, the road system is usually the predominant feature that ties them all together. Consequently, the landscape or region is precisely the right spatial scale for road system ecology, and for its ready applications in transportation planning, mitigation, and policy.

Related sciences, such as animal behavior, wildlife biology, plant ecology, forestry, population ecology, soil science, hydrology, water chemistry, aquatic biology and fisheries, are required and are usefully linked through landscape ecology. Furthermore, these must interdigitate with engineering and socioeconomics, including highway, forest-road, bridge and automotive engineering, as well as expertise in travel behavior, transportation economics, and transportation planning (National Research Council 1997).

The flourishing of road system ecology demands a body of theory and a body of solid empirical evidence. Promising bits of both exist. The broad objective of this article is to help accelerate the building of a body of theory by identifying together a range of spatial models useful in road ecology. Specifically eight models will be briefly outlined. Pondering will reveal numerous linkages and interactions among the models, a subject left for future discovery and elucidation.

These spatial models can be individually considered as theories, in the sense that each brings together disparate lines of evidence, is important and widely applicable, has predictive power, and is supported by some empirical evidence. Although presented as spatial models, only portions are briefly illustrated and outlined in language. Some can also be expressed as mathematical models, some as graphical models with curves on axes, and a few are perhaps still best expressed in language form. Fuller presentations of the models are given in the appropriate literature cited, and of course, additional models exist in road-system ecology literature.

Spatial Models

The eight models are introduced in the following order (Figure 1): (a) perforated roadbeds; (b) giant green network; (c) shrinking populations model; (d) road-effect zone; (e) node-and-network theory; (f) road-density/mesh-size; (g) network variability; and (h) ecological road fitting.

Figure 1. Diagrams illustrating portions of the eight spatial models. (a) Upper diagram with a wildlife overpass, three wildlife pipes, and a water-and-wildlife culvert; lower diagram with a wildlife underpass, a water-and-wildlife culvert, three amphibian tunnels, and three suspended systems for arboreal animals. (b) Only roadside strips of natural vegetation 10 to >100 m wide present; no vegetation patches. (c) A large vegetation patch with edges marked is bisected by a busy road, causing a sequential decrease in sizes of native populations located atAx@; H = habitat loss; E = edge effect; R = roadkills; D = disturbance avoidance zone; B = barrier effect subdividing small populations. (d) Each pair of arrows is a separate ecological variable with significant effects extending outward from a road; variables on left sensitive to slope, in middle to wind, and on right to suitability of the land. (e) A network with three node sizes and three corridor sizes. (f) High, low, and medium road density from left to right, and vice versa for mesh size of matrix patches. (g) Left to right, highest variance, largest patch, and largest average size of the few largest patches. (h) Roads marked by double line; dashed lines indicate less suitable routes to be avoided, which cross or destroy (generally left to right) stream headwater area, along streamsides, in riparian zone, mid-slope, hilltop, rare plant, rare habitat, through a large patch of natural vegetation, along edge of large patch, in middle of corridor connecting large patches, and rare animal.

Perforated roadbeds

Groundwater flows and surface water flowing in rivers, streams, and intermittent channels are frequently interrupted by road corridors or roadbeds, so the common solutions are bridges, culverts, and porous roadbed material (Stoeckeler 1965, Brown 1982, Gilje 1982, Swanson et al. 1988, Forman and Deblinger 1999). Excessive drainage may lead to a lowered water table, loss of wetland area, and reduced surface-water flows. On the other hand, inadequate drainage may produce a higher water table and spread of wetlands on the upslope side, while downslope the water table drops. Peak stream flows may also rise where roads intercept groundwater and channelize the water into surface flow (Jones and Grant 1996, Wemple et al. 1996). Therefore Aperforating roadbeds@ with an abundance of water crossing locations, rather than a few major crossings, normally would better mimic natural flows, as well as the resulting water-related habitats.

For a variety of reasons wildlife and other animals are generally inhibited in crossing roads. Indeed, different types of movement from foraging to dispersal and migration may be interrupted. This can result in an excess of animals on the source side of the road, and fewer animals on the destination side. However, more often roads affect animal populations through roadkills, avoidance of road disturbance, or creating small populations with demographic and genetic consequences. Although roads sometimes attract certain generalist species, overall the presence of roads blocking animal movement results in lowered population sizes. Perforating road corridors or roadbeds with an abundance of wildlife crossings helps overcome this disruption (Figure 1a). Furthermore, because affected animals come in many sizes, a range of wildlife crossing structures is important. Passages for small animals generally should be located to avoid water flow.

Structures or passages for wildlife crossing successfully operate in many countries, although the degree of success should be better evaluated. The following references provide an entrée into this subject: (1) amphibian tunnels (Langton 1989, Jackson 1996, Evink et al. 1996, Forman et al. 1997); (2) pipes for small and mid-sized animals (Mansergh and Scotts 1989, Natuur over Wegen 1995, Forman and Hersperger 1996, Friedman 1997, Canters 1997); (3) wildlife underpasses (Singer et al. 1985, Evink et al. 1996, Forman et al. 1997); and (4) wildlife overpasses (Natuur over Wegen 1995, Forman and Hersperger 1996, Forman et al. 1997, Friedman 1997).

Giant green network.

In intensive-agriculture landscapes few patches of natural vegetation typically remain. Instead the managed grassy roadsides may be the closest resemblance to natural vegetation present. In some cases they are managed in part for the remaining native species, which thus are rare species in the landscape (Aanen et al. 1991, H. van Bohemen, personal communication).

A more impressive case exists in many intensive-agriculture landscapes in Australia where Aroadside natural strips@, or road reserves, are protected (Figure 1b) (Saunders and Hobbs 1991, Bennett 1991, 1999). ATraveling stock routes@, which are widespread in New South Wales, are normally a few hundred meters wide. More abundant, however, in the Australian landscapes are major highways with natural strips exceeding 100 m width, secondary roads with strips several tens of meters wide, and small roads with some 10-30 m of adjacent natural vegetation. Roadside natural strips basically represent the little-used portions of the original road right-of-way. Many are actively managed for native vegetation and fauna.

The result is that these distinctive and distinct roadside natural strips often stretch for kilometers or tens of kilometers across the landscape, and provide extensive connectivity for nature. This remarkable phenomenon probably makes Australia the most connected ecological nation in the world.

The roadside natural strips form a giant green network (Figure 1b). It often does not connect species-rich patches, but rather biological diversity resides in the network itself. In general, the corridors cut through and include the range of microhabitat conditions in the landscape. Although few large patches of natural vegetation may be present and roads go down the center of almost all the corridors, the giant green network effectively holds a reservoir of native species in a connected system (Bennett 1999).

Shrinking populations model

A sequence of effects directly related to roads causes a shrinking of the sizes of natural populations (Forman and Alexander 1998). Consider a large species-rich patch of natural vegetation with a strip of edge around its border (Figure 1c). A road constructed through the patch causes direct habitat loss in the area of the road. An edge effect is quickly established in the adjoining vegetation, where edge microclimate and edge species predominate. Roadkills (faunal casualties) ensue as vehicles use the road. As traffic volume builds to thousands of vehicles or more per (commuter) day, a disturbance avoidance zone widens. Here, for example, ungulates and nesting of native birds markedly decrease (Rost and Bailey 1979, Reijnen et al. 1995, 1996).

Finally, the barrier effect resulting from the combined four preceding effects effectively subdivides the original large populations in the vegetation patch into small populations (Forman and Alexander 1998). For these small residual populations we can expect greater demographic fluctuation, more inbreeding, less genetic variation, and higher probability of local disappearance (extinction).

Road-effect zone

Roads affect numerous ecological factors, but most effects only extend outward meters or a few tens of meters from the road. However, some factors produce effects that extend far, e.g., >100 m or >1 km from a road. These delineate a Aroad-effect zone@ (Figure 1d) (Forman et al. 1997, Forman and Alexander 1998, Forman 1999a). A road slices through a land mosaic composed of different habitats, land uses, slopes, and wind directions. This means that the width of the road-effect zone varies widely, and that its boundaries are highly convoluted. Furthermore, the zone is asymmetric because water-transported materials tend to flow downslope, and wind-transported items tend to flow downwind. Also the suitability of the land, such as habitats, topography and spatial arrangement, differs on opposite sides of the road, so animal and human movement from the road differs in opposite directions.

The road-effect zone mapped for more than nine variables along a 25-km stretch of Massachusetts (USA) highway, is on average ca. 600 m wide, highly variable in width, asymmetric, and has convoluted boundaries (Forman and Deblinger 1998, 1999). The ecological flows across the broad landscape contrast strikingly with the detailed engineering dimensions in a narrow band along a road. Thus the road-effect zone delineates a promising common ground, the minimum zone for effective transportation planning (Forman and Deblinger 1999, Forman 1999b).

Node-and-network theory.

A body of network theory combining nodes and linkages evolved in the transportation field primarily for the economics of movement of people and goods (Figure 1e) (Taaffe and Gauthier 1973, Lowe and Moryadas 1975). Nodes of different sizes, such as cities, towns and villages, are included. A gravity model linking node size and distance apart was developed and later extended to address many problems, including traffic flow, hinterland analysis, and potential maps. Similarly linkages of different sizes such as major highways, secondary roads and local streets are included. Nodes can be sources and/or destinations, and routes can have capacities. Combining these variables into a network, which also can vary in many structural ways, creates a complex system indeed. Not surprisingly, dozens of spatial models and equations describing them have been described and used for different purposes. Examples include network connectivity, network circuitry, linkages per node, flows in a capacitated network, networks as valued graphs, graph-theory interpretation of hierarchies, nodal accessibility, and optimal transport pattern (Taaffe and Gauthier 1973, Forman 1995).

Most of the node-and-network theory appears to be beyond current ecological application. The existing theory basically only describes flows along the linkages or corridors; no movement into the enclosed spaces is permitted. Although an extensive ecological literature on the movement of species along corridors exists, few studies have yet shown movement of species along the connected corridors of a network. The limited evidence, e.g., of bats and insects moving along a network of hedgerows and stream corridors, does suggest that at least the simplest of the node-and-network models are useful. Thus network connectivity, network circuitry, and linkages per node (gamma, alpha, and beta indices) are considered to be ecologically meaningful (Forman 1995). In the future probably the gravity model will be found to be useful to understand species that move along connected corridors and are affected by patches of various sizes. Also the node-and-network models could be useful for understanding matrix species that move across corridors to the enclosed patches or spaces.

Road density/mesh size.

Several large mammal species have been related to road density. For example, wolves (*Canis lupus*) in Minnesota, Wisconsin, and Michigan (USA) and mountain lions (*Felis concolor*) in Utah (USA) appear to thrive where the road density is <0.6 km/km^2 (1.0 mi/mi^2) (van Dyke et al. 1986, Mech et al. 1988). The road density effect may be primarily due to roadkill, disturbance avoidance, or human access to remote areas, depending on the species and landscape (Forman et al. 1997).

Many other variables can be related to road density (Figure 1f) (Forman and Hersperger 1996, Forman et al. 1997). For instance, peak flows in mountain streams of Oregon (USA) tend to increase sharply at a road density exceeding ca. 3 km/km^2 (Jones and Grant 1996). Indeed, plotting large predator populations, fire size, fire frequency, peak flow in streams, and disturbance due to human access (using direct and indirect evidence from different regions) versus road density produces extremely different curves. This supports the hypothesis that a unique combination of ecological conditions can be associated with each road density level.

Mesh size is quantitatively the inverse of road density (Figure 1f). Since the absence of roads is the usual control for ecological conditions, mesh size describing the progressively smaller road-free area is probably the more appropriate measure. Although roads are sources of effects such as roadkills and anthropogenic fires, mostly road effects are effectively a constraining influence on the naturally functioning enclosed patch. Mesh size is apparently a useful single assay of ecological conditions in agricultural landscapes in France. In this case mesh size is of fields surrounded by hedgerows (Forman 1995). Owls, beetles, shrubs, herbaceous species, energy, soil and other conditions respond differently to mesh size.

Network variability.

Nature is spatially heterogeneous and irregular, and a perfect road grid imposed on it is in a sense the antithesis of nature. Where the mesh size is large relative to the ecological flows in the landscape, it may matter little whether the network is regular or irregular. However, most landscapes are crisscrossed by relatively fine-scale networks. Fortunately most contain variability. But what is the ecologically best way to be variable? Figure 1g shows three of the options: high variance; largest patch present; and largest average size of the few (four) largest patches. Indirect evidence for peak stream flow and for habitat area available to road-avoidance species was plotted for each of the three network variability options (Figure 1g), which varied from zero to high. Based on these two ecological variables the third option, i.e., the average size of the few largest patches, is hypothesized to be the ecologically best form of network variability.

Network variability is also important in adding and removing roads. If you were to add 10% of the road length (Figure 1g), e.g., in the ex-urban fringe area where residential development will continue, where would you place the new roads to best provide for ecological conditions? Or, if you were to remove 10% of the existing road length, e.g., in a forestry landscape where most of the easily cut timber has been harvested, what roads would you remove to best enhance ecological conditions? Solutions strongly depend on the nature of spatial variability in the road network.

Ecological road fitting.

Fitting the road network to the land is usually considered to be an engineering and economic problem. However, to accomplish both human mobility and environmental protection requires ecologically fitting the road to the land. In fact, building, removing, retrofitting, and mitigating roads in concert with landscape ecology is one of the most important steps in transportation. The challenge and solution is to locate roads relative to large vegetation patches, corridors of vegetation, rare habitats and species, streams and wetlands, and topographic sites (Figure 1h) (Harris and Scheck 1991, Forman 1995, Forman and Collinge 1997, Bennett 1999).

A map of the ecological network of a large landscape area is a *sine qua non* for effective planning. This is mainly the distribution of large natural-vegetation patches together with the major wildlife and water corridors (Natuur over Wegen 1995, Forman and Hersperger 1996, Forman et al. 1997). Including on the map the rare habitats and species, the relatively long-term ecologically impoverished areas (e.g., cities and industrial areas), and the shorter-term intermediate-suitability areas (such as cultivation and golf courses), makes the ecological network map much more useful. Then superimpose the road network on the ecological network. Bottleneck areas, where the roads interrupt ecological flows, are highlighted. Finally, use the array of mitigation measures available (Figure 1a) to eliminate bottlenecks. Ecological road fitting becomes a useful core of transportation planning.

Discussion and Conclusion

Other spatial models of road system ecology exist which range from having a well developed mathematical foundation to being current work. Graph theory has been used as a Acommon currency@ to convert landscape spatial patterns (including roads) into graph-theoretic graphs for comparison and for detecting widespread spatial patterns (Cantwell and Forman 1994). The effects of roads crossing other corridor types, such as streams, hedgerows and paths, has been briefly considered (Forman and Alexander 1998), and avian patterns have been related to traffic volumes on different road types of a network (R. Forman, B. Reineking and A. Hersperger, manuscript).

The models outlined here represent a preliminary foundation or body of theory for road system ecology. Although the emphasis is on spatial models, some can be expressed in other forms. The perforated-roadbeds and the ecological-road-fitting models at present are perhaps better expressed verbally in language. The node-and-network theory is equally well expressed as mathematical models or equations. The road density/mesh size and network-variability models can also be portrayed graphically as curves on axes. Spatial models (Figure 1) also offer visual and conceptual simplicity, which can catalyze communication among ecologists, engineers, economists, the public, and policy makers.

Although the models are presented separately, numerous interactions and feedbacks among the models exist. For instance, the perforated-roadbeds approach (Figure 1a) can affect two portions (roadkill and barrier effect) of the shrinking populations model (Figure 1c). Network variability (Figure 1g) is affected by the node-and-network arrangement (Figure 1e), and the ecological effects of both depend on road density/mesh size (Figure 1f). The road-effect zone (Figure 1d) can be much narrower, or wider, depending on the effectiveness of ecological road fitting (Figure 1h).

Many of the models can be directly linked to and used in present transportation planning and policy. The road-effect zone delineates the common meeting place between the central concerns of engineers and landscape ecologists. Ecological road fitting, by overlaying the road network onto the ecological network, identifies bottleneck and priority mitigation locations. Perforated roadbeds help solve conspicuous wildlife and water problems, and can generate considerable public interest and support.

Both objectives of transportation identified at the outset can be accomplished. Providing safe and efficient human mobility and also providing effectively for ecological flows and biological diversity are compatible. A solid science of road system ecology is essential and is emerging. It benefits from the recent development of landscape ecology, and promises to become one of the foundations of transportation planning and policy.

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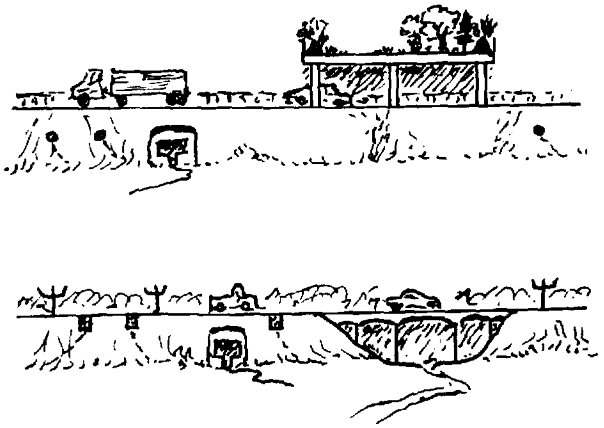
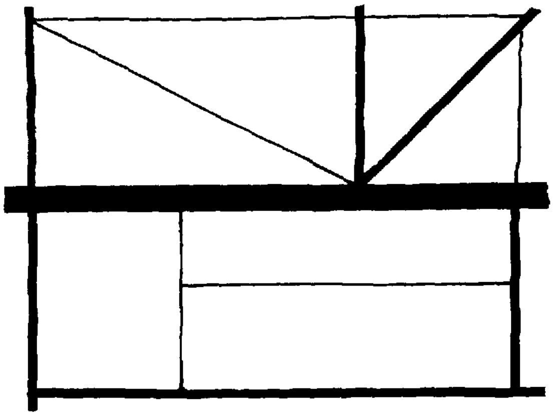
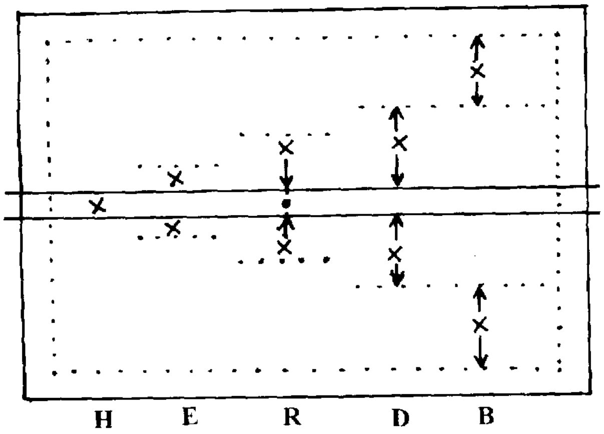
a. Perforated roadbeds



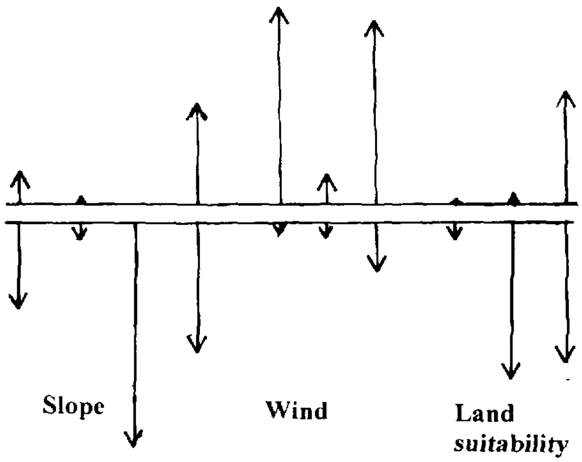
b. Giant green network



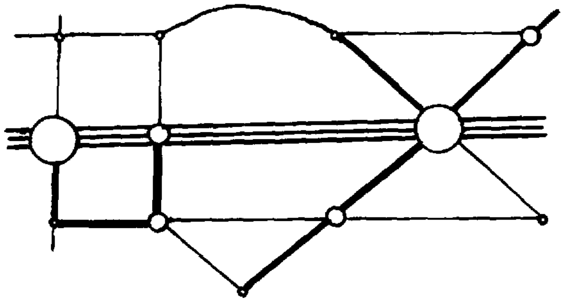
c. Shrinking natural populations



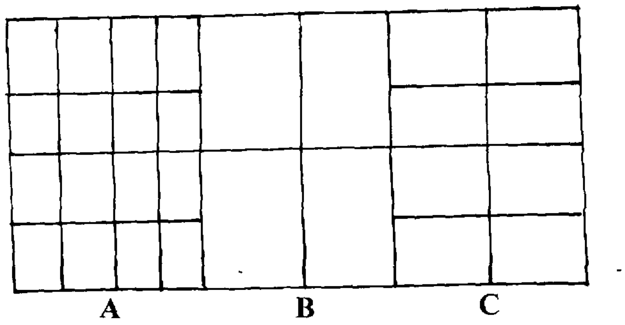
d. Road-effect zone



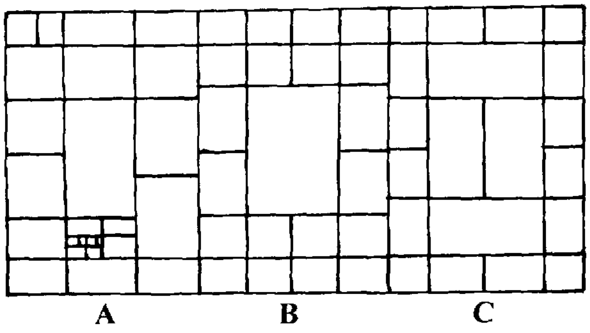
e. Node & network theory



f. Road density/mesh size



g. Network variability



h. Ecological road fitting