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Research Article

Road density and landscape pattern in relation to housing density, land ownership, land cover, and soils

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Abstract

Roads are conspicuous components of landscapes and play a substantial role in defining landscape pattern. Previous studies have demonstrated the link between roads and their effects on ecological processes and landscape patterns. Less understood is the placement of roads, and hence the patterns imposed by roads on the landscape in relation to factors describing land use, land cover, and environmental heterogeneity. Our hypothesis was that variation in road density and landscape patterns created by roads can be explained in relation to variables describing land use, land cover, and environmental factors. We examined both road density and landscape patterns created by roads in relation to suitability of soil substrate as road subgrade, land cover, lake area and perimeter, land ownership, and housing density across 19 predominantly forested counties in northern Wisconsin, USA. Generalized least squares regression models showed that housing density and soils with excellent suitability for road subgrade were positively related to road density while wetland area was negatively related. These relationships were consistent across models for different road types. Landscape indices showed greater fragmentation by roads in areas with higher housing density, and agriculture, grassland, and coniferous forest area, but less fragmentation with higher deciduous forest, mixed forest, wetland, and lake area. These relationships provide insight into the complex relationships among social, institutional, and environmental factors that influence where roads occur on the landscape. Our results are important for understanding the impacts of roads on ecosystems and planning for their protection in the face of continued development.

Introduction

Anthropogenic and natural disturbances, land ownership, land use, landforms, and land cover interactively define landscapes (Forman and Godron 1986). Within a given landscape, ecological processes affect and are affected by landscape patterns (Turner 1989). Roads are anthropogenic disturbances that impose distinct patterns on landscapes and influence a wide range of ecological processes (Forman and Alexander 1998). At the local scale, individual road segments change the physical and chemical environment, thereby causing habitat destruction or alteration, increasing the abundance of invasive species, interrupting hydrologic flows, and presenting barriers to species movements (Forman and Alexander 1998; Forman et al. 2003). At the landscape scale, roads cause fragmentation by removing habitat, creating high-contrast linear edges, and subdividing otherwise continuous habitat (Miller et al. 1996). Development and changes in land use near road corridors often cause further fragmentation (Dale et al. 1993; Turner et al. 1996).

Road density varies and some ecosystems are more fragmented by roads than others (Saunders et al. 2002). Yet high levels of landscape fragmentation do not necessarily occur with high road densities (Miller et al. 1996). The reasons for this are not clear. Past research on roads at the landscape level has largely focused on road patterns and how they affect ecological patterns and processes (Forman and Alexander 1998; Forman et al. 2003). In this paper, we seek a greater understanding of factors related to road density and the patterns created by roads at the landscape scale.

Studies of land use suggest that social, institutional, and economic factors play an important role determining land use and landscape pattern, while physical and ecological features of landscapes constrain land use and landscape pattern over space and across time. Examples of factors affecting landscape pattern include land ownership (Spies et al. 1994), housing density (Wear and Bolstad 1998; Radeloff et al. 2001), topography (Turner et al. 1996), soils and agricultural suitability (Dale et al. 1993), and lakes and wetlands (Walsh et al. 2003). The relative importance of factors depends on the scale of analysis (de Koning et al. 1998) and whether or not they are exogenous or endogenous to the system studied (Bockstael et al. 1995).

In their simplest form, road networks are primarily designed to connect local resources and people to distant markets and population centers (Dale et al. 1993; Ewing and Cervero 2001; Forman et al. 2003). Roads provide access and allow land use to occur (Dale et al. 1993; Turner et al. 1996), but changes in land use also induce new travel demands and create new transportation needs (Hess et al. 2001; Noland 2001). Land-use changes and the response to travel demands are mediated by political, social, and economic institutions that direct development to certain areas based on short and long-term goals (Ralston and Barber 1982; La Gro 1996; Robinson et al. in press). However, development may be constrained by environmental factors such as topography (Miller et al. 1996; McGarigal et al. 2001; Saunders et al. 2002). Advances in technology may decrease the relevance of constraints and initiate new phases of land-use change (Grubler 1994; La Gro 1996). Understanding the variation in road density and landscape pattern is no trivial task given the variety of factors involved in shaping the transportation network, their complicated interactions among factors, and their changing significance over time.

We tested hypotheses about the relationships among road density and landscape pattern to: housing density, land ownership, lake perimeter, land-cover classes, and soil substrate. For each factor, we hypothesized its relationship to both road density and landscape pattern generated by roads (Table 1). Because roads are constructed for a variety of purposes and different types of roads may not be affected equally by the same factors, we also tested our hypotheses for different combinations of road types (Table 2).

Methods

Study area

The heterogeneous landscape of northern Wisconsin allows examining a wide range of factors affecting road density and fragmentation. This heterogeneity is present in landforms, soils, vegetation types, land use, land ownership, and housing development, all factors that may influence road density and fragmentation.

The advance and retreat of the last major glaciation (9500–16,000 years ago) caused the current patterns of till deposits and landforms in the northern Great Lakes States (Martin 1965). The young forest soils that have developed since are highly variable, depending on the intricacies of glacial parent material (Hole 1976). Climate is characterized by snowy and cold winters with mild to warm summers. The average temperature is −11 °C in January and 19 °C in July; annual precipitation is 71–86 mm (Eichenlaub 1979).

The current forest vegetation of northern Wisconsin differs greatly from the landscape prior

Table 1. Hypothesized relationship between dependent variables: road density and landscape metrics to 13 independent variables.

	Road density					Landscape metrics		
	Classes 1–3	Classes 1–4	All classes	Class 4 only	Class 5 only	Proportion of area remaining	Median, mean, and maximum patch area	Area-weighted mean shape index
Road density	n.a.	n.a.	n.a.	n.a.	n.a.	–	–	–
Housing density	+	+	+	+	±	–	–	±
Public land	–	–	–	–	+	+	+	±
Lake perimeter	±	+	+	+	±	–	–	±
Land cover								
Agriculture	–	–	–	–	–	+	+	±
Grassland	–	–	–	–	–	+	+	±
Coniferous forest	+	+	+	+	+	–	–	±
Deciduous forest	±	±	±	±	±	±	±	±
Mixed forest	±	±	±	±	±	±	±	±
Wetland	–	–	–	–	–	+	+	±
Barren	+	+	+	+	+	–	–	±
Soil subgrade								
Excellent (AASHTO 1 and 3)	+	+	+	+	+	–	–	±
Good (AASHTO 2)	+	+	+	+	+	–	–	±
Poor (AASHTO 4, 6, 7, and 8)	–	–	–	–	–	+	+	±

(+) Indicates a hypothesized positive relationship, (–) a hypothesized negative relationship, (±) indicates relationship is unknown, n.a. indicates the variable is not applicable.

Table 2. USGS road class definitions (USGS 1998).

Road class	Description
1	Hard-surface highways including Interstate US numbered highways (including alternates), primary State routes, and all controlled access highways
2	Hard-surface highways including secondary State routes, primary county routes, and other highways that connect principal cities and towns, and link these places with the primary highway system
3	Hard-surface roads not included in a higher class and improved loose-surface roads passable in all kinds of weather. These roads are adjuncts to the primary and secondary highway systems. Also included are important private roads such as main logging or industrial roads which serve as connecting links to the regular road network
4	Unimproved roads which are generally passable only in fair weather and used mostly for local traffic. Also included are driveways, regardless of construction
5	Unimproved roads passable only with 4-wheel-drive vehicles

to European settlement (Mladenoff et al. 1993; Radeloff et al. 1999), when it was a mix of largely old-growth and mature hemlock (*Tsuga canadensis*) northern hardwood and pine forests, conifer swamps, and pine and oak barrens (Curtis 1959). Logging started in the late 1800s, reached a peak around 1890, and declined since. Open land was often converted for agriculture, but most farms were short lived, failing due to climate and soil nutrient depletion. Many private lands had reverted to public ownership by the 1920s and were reforested. Current land ownership is a mix of 15% county forests (Wisconsin County Forests 2003), 5.5% state land (Wisconsin Department of Natural Resources 2002), 16% National Forest (U.S. Forest Service 2001), 4.5% tribal nations (J. Coleman, Great Lakes Indian Fisheries and Wildlife Consortium, personal communication). The remaining 59% of land area is in private ownership. Today, forests are largely dominated by sugar maple (*Acer saccharum*) or early successional species such as aspen (*Populus* spp.) (Mladenoff et al. 1993; White and Mladenoff 1994). Timber production remains significant, but the economy is largely driven by tourism and recreation (Flader 1983).

Between 1940 and 1990, the human population increased from 344,570 to 365,344 in the 19 counties comprising our study area, and the number of houses increased from 106,378 to 230,700 (US Bureau of the Census 1991). Housing growth was strong in areas rich in natural amenities and in close proximity to lakes; especially in the pine barrens in northwest Wisconsin (Radeloff et al. 2001) and the northern highlands in north central Wisconsin (Schnaiberg et al. 2002). Continued growth in rural housing is expected to continue in the future (Radeloff et al. 2001; Hammer et al. 2004).

When Wisconsin achieved statehood in 1848, it inherited a very limited system of roads that has since undergone drastic changes to become the modern road system we know today (Betchel 1989; Davis 1989). Originally, the state and federal governments had little involvement in road planning, finance, construction, or maintenance. Federal and state involvement in the road network increased overtime as they designated federal and state highway routes and provided construction standards and matching funds. In 1976, the Wisconsin Legislature adopted a policy to maintain existing roads and only build new roads when necessary (Betchel 1989). Currently, roads are funded and managed by municipalities, townships, counties, state and federal agencies as well as private land owners.

Sample design and data sources

Our study area (Figure 1) included predominantly forested (60% or greater cover) counties in northern Wisconsin USA. Generally available road data, such as US Census Bureau TIGER or U.S. Geological Survey (USGS) Digital Line Graphs (DLG), are incomplete and miss up to 50% of roads present on the landscape (Hawbaker and Radeloff 2004). Therefore, 10% of each county's area was sampled by randomly selecting non-overlapping quadrangles from a grid covering the study area. Each sample unit, or quadrangle, covered area of approximately 3500 ha, equivalent to a USGS Digital Orthophoto Quarter-quadrangles (DOQQ), or 1/4 of the area covered by a

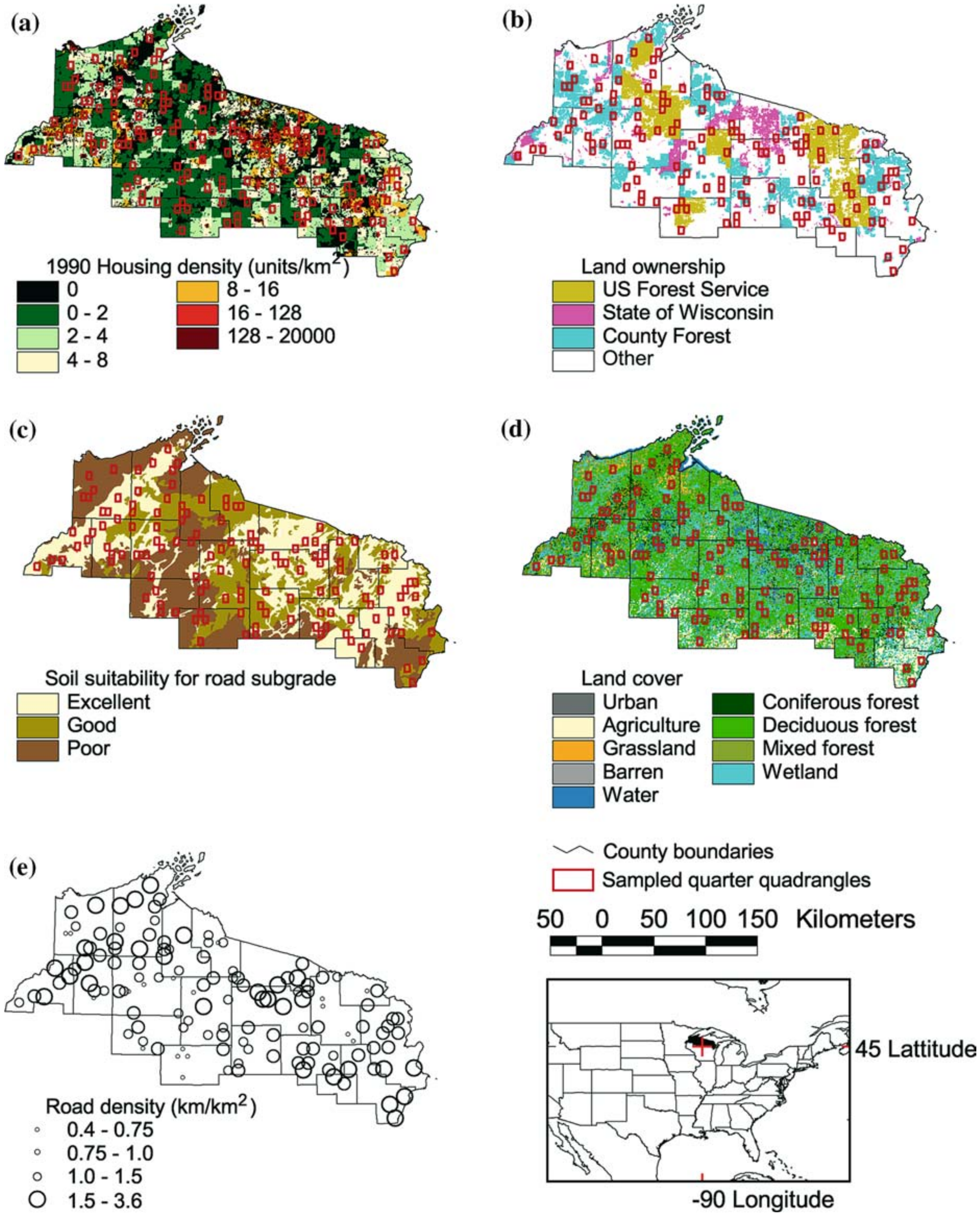

Figure 1. Data sources used in generalized least squares models of road density and landscape pattern: (a) 1990 US Census housing density, (b) public land ownership, (c) STATSGO soil suitability for road subgrade, (d) land-cover classification derived from LANDSAT imagery, and (e) road density as mapped from aerial photography. Circles are centered on sample units and increase in size with road density. Legend breaks follow quartiles in road density data distribution.

USGS 1:24,000-scale topographic map (USGS 1996). The total sample was 134 quarter-quads, or roughly 469,000 ha.

We digitized unmapped roads, visible in digital orthophotos and added them to existing Digital Line Graph (DLG) road data (USGS 1998). The digital orthophotos were 1:40,000-scale black and white aerial photographs with 1-m pixel resolution taken between 1986 and 1999. We considered roads to be any linear feature that was connected to existing roads and had clear evidence of vehicular use. Roads less than 50 m in length (e.g., short driveways) were not mapped.

The ecological effects of roads vary with the type of road, vehicular use, and maintenance (Forman and Deblinger 2000; Lugo and Gucinski 2000). We assigned all roads a class according to the USGS road classification system (Table 2). Road density was calculated as the length of roads divided by the terrestrial area for the 134 sampled quarter-quads. Density was calculated for all roads, road classes 1–4, and classes 1–3 combined, and classes 4 and 5 roads individually.

We examined landscape patterns created by three different combinations of roads paved roads (classes 1–3), paved and unimproved roads used for local traffic (classes 1–4), and all roads (classes 1–5). Each road was buffered (Bernhardsen 1999) according to road class using an average road widths measured from 30 randomly selected points along roads in aerial photographs (Table 3). The same buffer distance was applied to classes 1 and 2 roads, as a *t*-test for comparison of means assuming unequal variance provided little evidence against the hypothesis that the difference in width was equal to 0 (p-value = 0.153), (Table 3). After roads were buffered, we calculated landscape metrics for terrestrial patches outside the road buffers for each quarter-quad.

Table 3. Road width by road class as measured from aerial photographs using 30 points along randomly selected road segments for each road class.

Road class	Mean roadway width (m)	Standard deviation (m)
1 and 2	32.0	14.3
3	15.7	7.9
4	9.9	5.3
5	4.8	1.9

Width of classes 1 and 2 roads was not significantly different (t-test for difference = 0, n = 30, p-value = 0.153), and the two classes were considered equal.

We measured habitat availability using the proportion of non-road area remaining after roads were buffered (sum of patch areas/total terrestrial area). Habitat fragmentation was measured using median, mean, and maximum patch area (ha). Sum of patch perimeters was calculated as a measure of edge (km) and patch shape was quantified using the area-weighted mean shape index (awshp), a measure of the ratio of perimeter (p) to area (a) for individual patches weighted by the size of the patch (a) relative to the total area of all patches in the landscape (A) (Eq. (1)).

$$\text{awshp} = \frac{p}{2\sqrt{\pi a}} \times \frac{a}{A}$$

The landscape metrics we selected were chosen because of their ability to describe variation of patch sizes, ecological significance (Forman and Godron 1986), and lack of correlation among them (Riitters et al. 1995). Additionally, previous road studies have used similar metrics making our results more comparable (Miller et al. 1996; Reed et al. 1996; Tinker et al. 1998; McGarigal et al. 2001; Saunders et al. 2002).

Metrics were calculated for each quarter-quad and then averaged across all quarter-quads for each road class combination. Patch-area distributions were skewed at two levels, within quarter-quads and among quarter-quads. We report median, mean, and maximum areas to describe this distribution within quarter-quads. However, after median and mean patch areas were averaged across all quarter-quads, they were natural log transformed to produce the normal distribution required by statistical assumptions underlying regression models (Chatterjee et al. 2000).

Block level 1990 US Census data (US Bureau of the Census 1991) were used to calculate housing density for each quarter-quad sampled. These data were natural log transformed to achieve a normal data distribution. Landowner information was quantified as the relative area of public land in each quarter-quad (US Forest Service 2001, Wisconsin Department of Natural Resources 2002).

Land-cover variables were derived from classified multispectral Landsat satellite imagery (Wisconsin Department of Natural Resources

1998). We calculated the area of deciduous forest, mixed forest, coniferous forest, wetland, agriculture, grassland, and barren land-cover classes within each quarter-quad. Lake area and perimeter were measured using the 1:24,000-scale polygon hydrology coverage (Wisconsin Department of Natural Resources 2001). To achieve normality, wetland area was square root transformed, and agriculture, grassland, coniferous forest, mixed forest, and barren land were log transformed.

Soil suitability for road subgrade was determined using the STATSGO soils database (Natural Resources Conservation Service 1991). For each sampled quarter-quad, we calculated the percent volume using a maximum soil depth of 60 cm for each of the seven American Association of State Highway Transportation Officials soil subgrade classifications (Caduto 1999). Percent soil volumes were combined into three general categories: excellent (A1 and A3), good (A2), and poor (A4, A6, A7 and A8) because some classifications occur in low frequency or were not present (A5).

Model development and validation

We used generalized least squares (gls) regression models (Pinheiro and Bates 2001) to explore the hypothesized relationships between road density and independent variables (Table 1). Since we assumed all variables would have an equal chance of affecting road density and pattern, we started with all variables in models and removed variables coefficient p-values greater than 0.05 using a backwards elimination procedure. Backwards, or stepdown elimination has significant advantages over forward and stepwise selection schemes. It is possible for a set of variables to have considerable predictive capability even though any subset of them does not. If variables do not predict well individually, then they will not enter the model under forward selection and stepwise regression may fail to identify them (Mantel 1970). Model improvement during backward elimination was measured using Bayesian Information Criterion (BIC) and overall model fit was judged using residual standard error.

Once variable selection was complete, we examined model residuals to validate the assumptions of least squares models: normally distributed errors, constant variance, and independent observations (Chatterjee et al. 2000). The assumption of independence is difficult to meet in ecological studies since many environmental variables may exhibit spatial and temporal dependence or autocorrelation (Rossi et al. 1992). The presence of autocorrelation in model errors affects regression coefficients by underestimating standard errors; as a result, confidence intervals are underestimated, producing false measures of significance (Chatterjee et al. 2000). We tested for spatial autocorrelation in model residuals using a variogram fitting procedure (Pinheiro and Bates 2001). The easting and northing coordinates of each quarter-quad polygon center-points were used for spatial locations. The effects of spatial autocorrelation can be eliminated by including correlation structures modeling the spatial dependence of errors in the regression model (Pinheiro and Bates 2001). If spatial autocorrelation was detected, we developed a second gls model that included a spatial correlation structure. The significance of the spatial correlation on model improvement was tested using an ANOVA procedure between the two models (Pinheiro and Bates 2001). This modeling procedure was used first to relate total road density to the independent variables. Additional models were constructed with each using the density of classes 1–4, classes 1–3, class 4, and class 5 roads as dependent variables.

Similar models were developed for metrics of landscape patterns created by all roads, classes 1–4 roads, and classes 1–3 roads. Variables with greater than 60% correlation among them were not included in models. However, road density was always included in landscape metric models if significant, regardless of its correlations with other variables. By doing so, the effects of other factors can be interpreted while taking into account the effects of road density.

Results

Road density models

The correlations between independent variables and road density varied among the different combinations of road classes (Figure 2). The density of improved roads (classes 1–3) and local

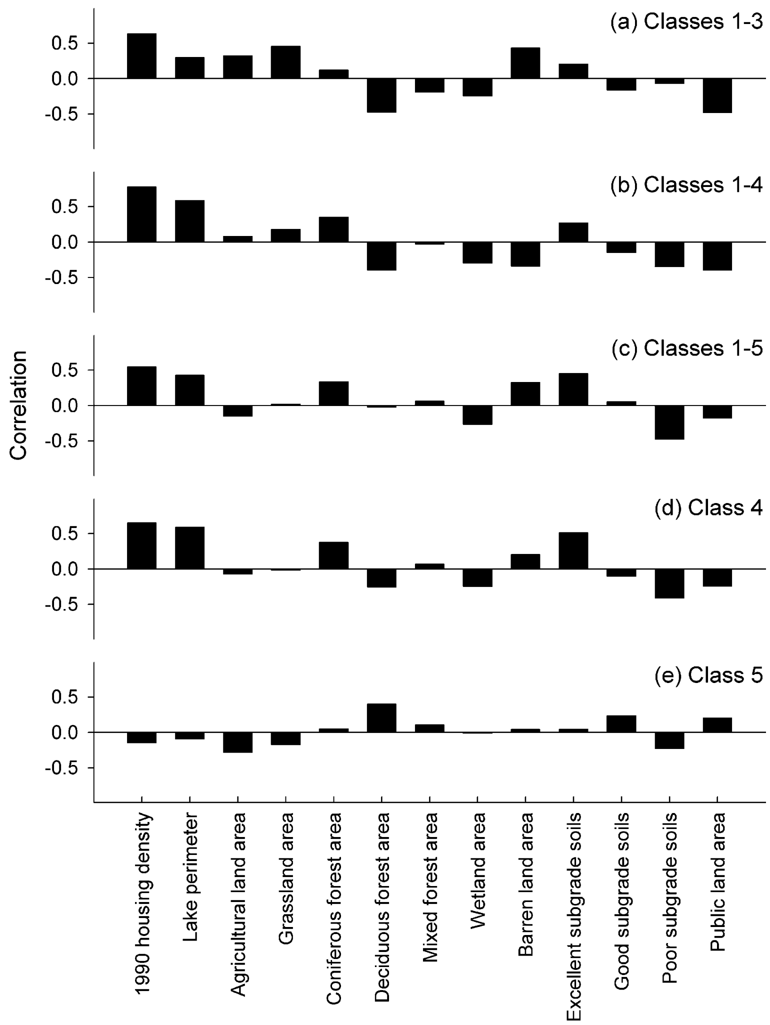

Figure 2. Correlations between road density and independent variables used in generalized least squares models. (a) Roads of classes 1–3 combined, (b) roads of classes 1–4 combined, (c) classes 1–5 combined, (d) class 4 roads only, and (e) class 5 roads only.

unimproved roads (classes 1–4 and class 4) was positively correlated with housing density, lake and coniferous forest area, and the percent volume of excellent subgrade soils, but negatively correlated with deciduous forest and wetland areas, percent volume of poor subgrade soils, and public land area. The sign of the correlation varied among road class combinations for percent volume of good subgrade soils, agricultural land, grassland, mixed forest, and barren area. For example, housing density and lake perimeter were positively correlated with road density for most road class combinations, but negatively correlated with class 5 road densities. A similar switch in the direction of the correlation was found for deciduous forest area, percent volume of good subgrade soils, and public land area (Figure 2).

Generalized least squares models indicated which of the independent variables were significant factors in explaining road density. Variables that had significant positive regression coefficients across all road class combinations included housing density, and grassland, mixed forest, and barren area, and percent volume of excellent subgrade soils. Only agricultural and wetland area had significant negative regression coefficients (Table 4). The effects of lake perimeter and deciduous forest area varied depending on the classes of roads used in the model.

Table 4. Final generalized least squares (gls) regression road density model coefficients and significance after backwards elimination of variables.

	Classes 1–3 roads	Classes 1–4 roads	Classes 1–5 roads	Class 4 roads	Class 5 roads
Intercept	**0.55**	***1.20***	***1.85***	−0.25	0.32
ln(1990 housing density + 1)	***0.15***	***0.56***	***0.52***	***0.38***	
Lake perimeter (km)		**0.01**		**0.01**	*−0.01*
ln(agricultural land area + 1)			***−0.14***		***−0.13***
ln(grassland area + 1)	*0.06*				
Deciduous forest area (ha)	< ***−0.01***	< *−0.01*			< ***0.01***
ln(mixed forest area + 1)				*0.07*	
sqrt(wetland area)	−0.01	***−0.02***	*−0.02*	−0.01	
ln(barren land area + 1)	0.03		*0.12*		*0.11*
Excellent subgrade soils		0.62	***1.73***	0.61	**1.14**
Variogram form	expon.	expon.	expon.	None	Linear
Range (m)	13,500	22,960	9362		11,258
Nugget	0.49	0.46	< 0.01		0.01
p-Value	0.06	< 0.01	< 0.01		0.01
Residual standard error	0.22	0.45	0.62	0.42	0.60

Significance of variable coefficient: ***p ≤ 0.0001***, **p ≤ 0.001**, *p ≤ 0.01*, p ≤ 0.05. Exponential variograms are labeled as expon. Variogram *p*-values represent the significance of ANOVA test between spatial and non-spatial models.

Landscape pattern models

Variables positively correlated with fragmentation included road density, housing density, lake perimeter, lake area, and grassland, coniferous forest, and barren area (Figure 3). Deciduous forest, wetland, public land area, and percent volume of poor subgrade soils were negatively correlated with fragmentation. Other variables had inconsistent correlations, switching between positive and negative correlations for different road class combinations. Agricultural area and percent volume of excellent subgrade soils were generally positively correlated with fragmentation measures, but the response was different among road combinations for maximum patch area. Mixed forest area and percent volume of good subgrade soils were negatively correlated with fragmentation measures, but positively correlated for area-weighted mean shape index (Figure 3).

We considered landscape fragmentation as the process of reducing proportion of area remaining, median, mean, and maximum patch areas, but increasing patch perimeters, and area-weighted mean shape indices. As expected, road density was almost always the most significant factor explaining landscape patterns in the generalized least squares models (Table 5). Regardless of the classes of roads used to generate landscape pattern, road density was always negatively related to non-road patch areas (mean, median, and maximum), but positively related to sum of patch perimeter (Table 5 and Figure 3). Road density was positively related to area-weighted mean shape index of patches only when roads of classes 1–4 were used to define patch boundaries (Table 5). As road density increased, patch perimeter increased, and the proportion of area remaining and median, mean, and maximum patch area decreased.

Housing density was negatively correlated with the proportion of area remaining, maximum patch area, mean patch area, and positively correlated to the sum of patch perimeters (Table 5). However, housing density was included in few models because of its high correlation with road density. When housing density was a significant factor, areas with high housing density had a smaller proportion of the total terrestrial area in non-road patch area. When roads of classes 1–3 were used to define patch boundaries, mean patch area was greater in areas with higher housing density. However, when classes 1–5 roads were used to define patches, mean patch area decreased with housing density. Sum of patch perimeter was positively related to housing density for roads classes 1–5.

Differences in landscape pattern were also related to land-cover variables. Increases in the

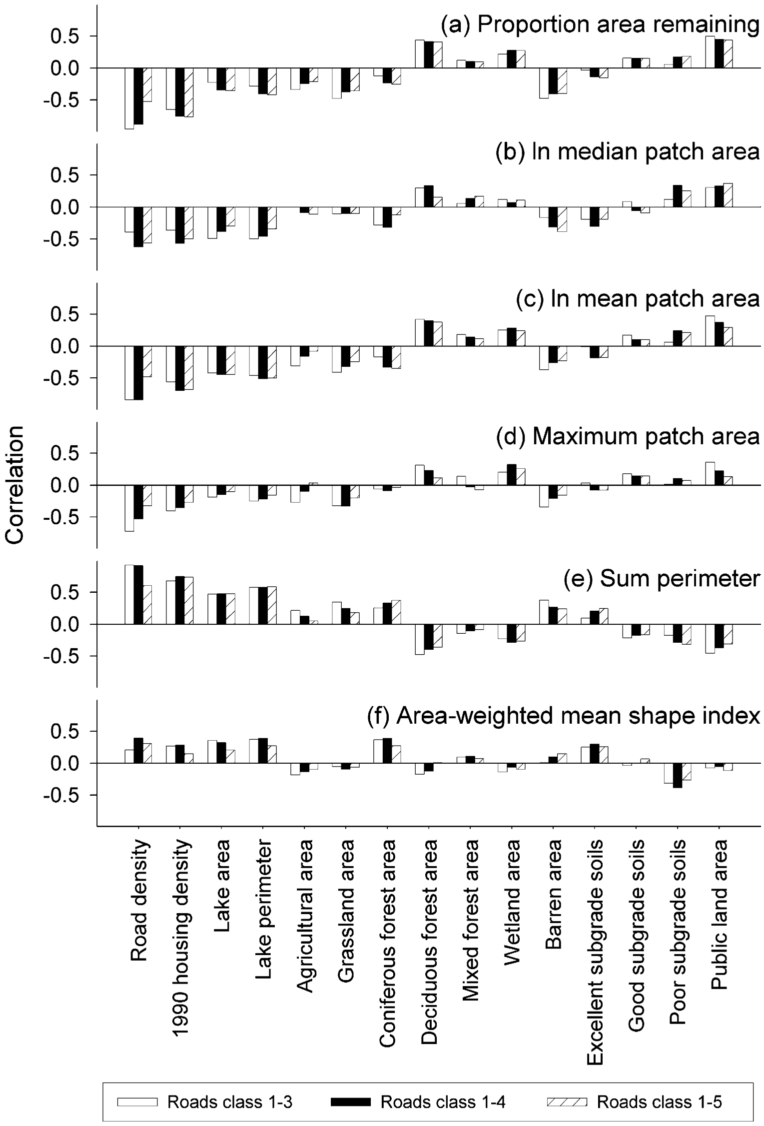

Figure 3. Correlations between independent variables used in generalized least squares models of landscape metrics. (a) proportion of terrestrial area remaining outside buffered roads, (b) median patch area, (c) mean patch area, (d) maximum patch area, (e) sum of patch perimeter, and (f) area-weighted mean shape index of non-road patches. Road class combination indicates the types of roads used to define patch boundaries.

amount of land under agricultural use resulted in greater landscape fragmentation. Grassland and agriculture area were negatively related to patch-area metrics, while sum of patch perimeter was positively related, and no significant relationship was found with area-weighted mean shape index (Table 5).

Landscape patterns differed depending on the type of forests and the types of roads used to define pattern. Coniferous forest area was negatively related to median and mean patch area and positively related to area-weighted mean shape index (Table 5). Deciduous forest area was negatively related to medium and maximum patch area and the proportion of area remaining. Relationships with mixed forest area differed among combinations of road classes. For classes 1–3 (improved) roads, the proportion of area remaining was negatively related to road density, but for classes 1–4 roads, mixed forest area was negatively related to

Table 5. Final generalized least squares regression model coefficients and significance for landscape metrics of patches outside buffers generated using different combinations of roads classes.

Road classes	Ratio of total patch area to total terrestrial area			Log-transformed median patch area			Log-transformed mean patch area		
	1–3	1–4	1–5	1–3	1–4	1–5	1–3	1–4	1–5
Intercept	***1.01***	***1.01***	***1.00***	*7.47*	***5.31***	***3.22***	***7.56***	***7.26***	***6.28***
Road density (km/km^2)	***−0.02***	***−0.01***	*< −0.01*	**−0.79**	***−0.79***	***−0.39***	***−1.62***	***−0.72***	−0.13
ln(1990 housing density + 1)	*< −0.01*	*< −0.01*	< ***−0.01***				**0.18**		***−0.43***
Lake area (km^2)		< 0.01	< 0.01	< ***0.01***			< ***−0.01***		
Lake perimeter (km)			< −0.01						*−0.01*
ln(agricultural land area + 1)							−0.04		
ln(grassland area + 1)	*< −0.01*	< ***−0.01***	*< −0.01*				−0.07	***−0.12***	
Coniferous forest area (ha)				−0.12				*−0.08*	
Deciduous forest area (ha)			**0.00**		< 0.01				
ln(mixed forest area + 1)	< **−0.01**							*0.06*	
sqrt(wetland area)			*< 0.01*						
ln(barren land area + 1)					−0.06				
Excellent subgrade soils	*< −0.01*	−0.01	*−0.01*		−1.62				
Poor subgrade soils	< −0.01	**−0.01**	−0.01						
Public land				< 0.01		< **0.01**			
Variogram form	None	None	None	None	None	None	None	None	expon.
Range (m)									60,376
Nugget									0.54
p-Value									
Residual standard error	0.00	0.00	0.00	0.99	1.05	0.55	0.32	0.37	0.51

Table 5. Continued.

	Maximum patch area			Sum patch perimeter			Area-weighted mean shape index		
	1–3	1–4	1–5	1–3	1–4	1–5	1–3	1–4	1–5
Intercept	***2721***	***2457***	***1034***	***22.57***	***34.13***	***46.51***	***1.11***	***1.67***	***1.77***
Road density (km/km^2)	***−1581***	***−351***	*−143*	***58.42***	***37.97***	***9.63***		*0.20*	
ln(1990 housing density + 1)						***20.11***			
Lake area (km^2)				***−0.03***	***−0.05***	**−0.07**	*< 0.01*		
Lake perimeter (km)						0.61			
ln(agricultural land area + 1)									
ln(grassland area + 1)		**−116.71**		1.02	*3.32*				
Coniferous forest area (ha)							*0.11*	0.09	**0.11**
Deciduous forest area (ha)			0.14						
ln(mixed forest area + 1)					−1.79				
sqrt(wetland area)			*13.22*						
ln(barren land area + 1)					−1.86				0.06
Excellent subgrade soils									
Poor subgrade soils								−0.63	
Public land									
Variogram form	None	None	None	None	None	expon.	None	None	None
Range (m)						47,888			
Nugget						0.39			
p-Value						***0.00***			
Residual standard error	524.20	483.59	482.71	5.10	12.68	21.12	0.48	0.54	0.49

Significance of variable coefficient: coefficient: ***p ≤ 0.0001***, **p ≤ 0.001**, *p ≤ 0.01*, p ≤ 0.05. Exponential variograms are labeled as expon. Variogram *p*-values represent the significance of ANOVA test between spatial and non-spatial models.

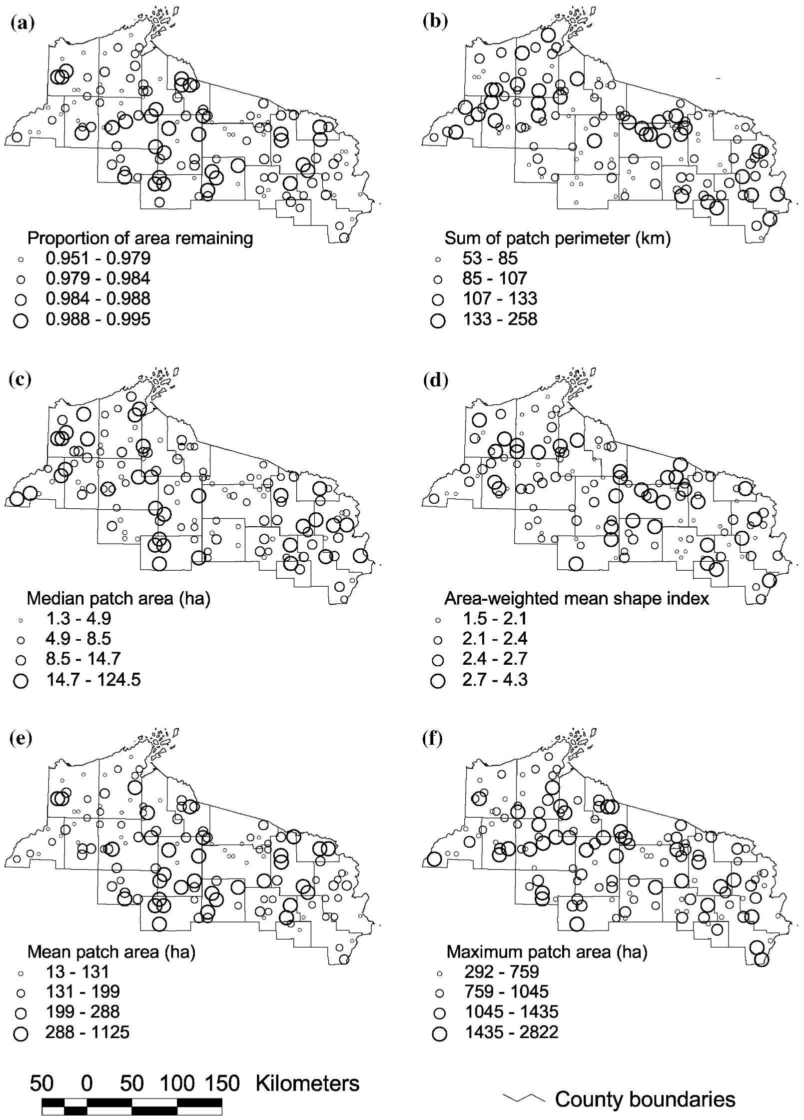

Figure 4. Maps summarizing landscape pattern of terrestrial patches outside buffered classes 1–5 roads: (a) proportion of area, (b) sum patch perimeter, (c) mean patch area, (d) area-weighted mean shape index, and (e) largest patch area in the 134 sample units. Circles are centered on sample units. Legend breaks follow quartiles in data distributions.

sum of patch perimeter and positively related to mean patch area. When all roads were used to define patch boundaries, wetland area was positively related to largest patch area and the proportion of area remaining (Table 5).

Lake perimeter was only significant in models of class 5 road patterns (Table 5). Total of patch perimeters increased with lake perimeter and proportion of area remaining and mean patch area decreased with lake perimeter. Correlations between lake area and sum patch perimeter were positive (Figure 3), but had a negative coefficient in the regression models (Table 5). This may be an effect of overlap between road buffer perimeters and lakes, affecting perimeter by eliminating part of buffers falling within lakes. Similar responses were found with soil subgrade variables; the coefficients for both excellent and poor subgrade had the same direction (Figure 3 and Table 5).

Spatial autocorrelation in models

All but one of the road density models had a significant spatial structure in their residuals

(Table 4), while only 2 out of the 15 landscape pattern models had significant spatial autocorrelation (Table 5). By including spatial correlation structures in our final models, we nullified the effects of spatial autocorrelation on the significance of regression coefficients.

Discussion

Roads are ubiquitous features of landscapes and have a wide range of ecological effects (Forman et al. 2003). A greater understanding of which factors affect road networks is needed to represent the complexity of land-use systems and linkages between human and environmental systems. Our results show that environmental variables and housing density development are significantly related to the distribution of road densities and landscape patterns created by roads, while land ownership had no significant relationship. Across the different combinations of road classes, three variables consistently appeared in models of road density: housing density and soils with excellent road subgrade suitability were positively correlated with road density, while wetland area was negatively correlated (Table 4). In models of landscape metrics, road density explained the largest portion of variation in landscape patterns, but other factors were significant depending on the metric and the type of roads examined (Table 5).

The significance of variables in both models of road density and landscape patterns changed with different road class combinations. This reflects the variety of reasons for which different roads are constructed. Greater densities of improved roads (classes 1–3) that provide the primary transportation routes among large population centers were found in areas with greater housing density, grassland and barren land area. Road density declined with increasing wetland and deciduous forest area (Table 4). Densities of class 4 roads, which typically provide access to lakeshore cabins and housing development, but also include primary logging routes, increased with housing density, lake perimeter and mixed forest area, and decreased with wetland area (Table 4). Density of class 5 roads, which are primarily logging roads and jeep trails were not significantly related to housing density, but were correlated with land cover and soils (Table 4).

Our approach relating road density with housing density, land cover, land ownership and soils is well suited to reveal statistically significant relationships, but it does not identify what are causal factors and what is effect. Some of the significant environmental factors that we identified are in all likelihood causal factors. Wetlands have likely acted as constraints to road development while soils that provide excellent subgrade permitted easy road construction. Housing density has a more complex relationship with road density, where one factor influences the other. Our analysis can not address the question 'which came first, houses or roads?' Long-term and detailed time series on both road and housing development would be necessary to address this question. However, even a long-term dataset may not suffice to separate cause and effect in housing and road development because the two are intrinsically related. In order for housing development to occur, it requires either existing roads, or construction of roads to provide land access. However, just the fact that housing development is planned in an area may be enough for road construction to proceed and roads may be constructed in order to foster development. Additional roads may be constructed in response to new travel demands and land-use change after housing development has occurred. Our results highlight the strong relationship between housing density and road density, but they do not identify how one is affecting the other.

Land ownership and environmental factors can have complex relationships with landscape patterns (Crow et al. 1999). However, our models suggest public lands have little power explaining variation in road density and landscape patterns created by roads at the scale of our 3500-ha sample units, even though road density was greater on public lands in our study area (3.1 km/km^2 vs. 2.7 km/km^2). Median patch area was the only metric that had significant (positive) relationships with the relative proportion of public land (Tables 4 and 5). Housing density was inversely related to the relative proportion of public land and in our models of road density and landscape pattern housing density consistently explained more variation than the relative area of public land.

Legacies of settlement and land use may have played a large role in shaping current road patterns (Mladenoff et al. 1993; Crow et al. 1999).

Many public lands in northern Wisconsin were established in the 1920s and 1930s through purchases of private and tax-forfeited lands (Flader 1983), and the landscape patterns created by roads may have been established before the public lands existed. Following establishment public lands were not immune from road development. Forest management and private land inholdings both require road access and regional patterns of development may have necessitated the construction of roads through public lands.

Care must be taken in applying our results to other regions. The general relationships we found among road density and landscape patterns created by roads with housing density, soils, and land cover are likely to hold in other regions, but the relative importance among factors may change and additional factors may be important. For instance, in areas with greater topographic relief, elevation is an important factor determining road routes. Alternatively, different land uses and different landscape histories may cause different road network configurations and levels of fragmentation. For example, the public lands in the western US were established before extensive settlement and are much less fragmented than in the eastern US. In spite of these potential differences, we believe our research findings are relevant to forested regions throughout the eastern US.

The results of our analysis may depend on the grain of the data sources used and the scale of the sample units. The grain of our data ranged from 30-m pixels in the Wiscland satellite image classification to STATSGO soil polygons with minimum mapping unit of 625 ha (Natural Resources Conservation Service 1991), census blocks varied in size according to housing density, and landowner data were limited to 16 ha (40 acre) mapping units. We aggregated data to the scale of quarter-quads ($\sim$3500 ha), reducing fine-scale variation (Jelinski and Wu 1996). Somewhat different results might be expected if our hypotheses were tested using data or sample units with different grain sizes.

Previous studies of roads and landscape pattern have shown variable results among different scales. In one study, the effect of roads on landscape pattern changed between two different scales (Saunders et al. 2002). At finer scales, fine environmental factors such as land cover have a greater influence on the path a road takes across the landscape. At broader scales, these environmental factors may be less important than broad social patterns (Forman et al. 2003). In any case, we would expect the positive relationships we found between road density and pattern with housing density, soil suitability and the negative relationship with wetland areas to be consistent across a range of both finer and coarser scales of analysis.

Regional planning, zoning and growth laws were not considered in our analysis. We do not suggest that they are not relevant, but that they are challenging to study using a quantitative approach because they vary considerably across our study area, because they are not stable over time, and because it is unclear if plans are actually implemented as written. For instance, restrictive zoning laws may fail to prevent development when stakeholders can subdivide land before laws go into effect (Thorson 1997) and even when zoning laws exist, they can be circumvented by variances and extractions that allow for unplanned development (Last 1995 as cited in La Gro 1996; Thorson 1997). Part of the challenge in developing effective zoning and land-use planning is to appeal to the desire of people to connect with the land. Many small landowners engage in activities with little or no economic benefit (Koontz 2001). Unless peoples desire to connect with the land is met through other opportunities, growth limiting laws will have unintended consequences beyond their boundaries and continue to contribute to low-density sprawl and habitat fragmentation (Robinson et al. in press).

Existing zoning laws need consistent implementation in order to limit fragmentation (La Gro 1996). Purchase and transfer of development rights offer promising opportunities to protect land and limit fragmentation (Brabec and Smith 2002). Clustering development (Theobald et al. 1997), calming traffic (Jaarsma and Willems 2002), and decommissioning existing roads (Miller et al. 1996) also holds promise to limit the fragmenting effects of houses and roads. These methods need to specifically address road development in conjunction with land use and be implemented in coordination with each other to protect existing undisturbed areas and incorporate and restore imperiled habitat types.

Ultimately, broad-scale approaches across public and private lands that addresses past, current, and projected future patterns of land use and settlement are necessary to reduce the fragmenting effects that roads have on landscape pattern.

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