Sustainable Transport Planning: Estimating the Ecological Footprint of Vehicle Travel in Future Years

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Abstract: An important indicator of sustainable land use, the ecological footprint measure has proved unsuitable for many planning applications because of the limited availability of impact data at the local level of cities and counties and because of an inability to estimate the ecological footprint of future development scenarios. In light of these limitations, this paper presents a methodology for measuring the ecological footprint of a county-level transportation network in current and future time periods. With the aid of vehicle travel behavior and fleet characteristics obtained from a number of state and federal agencies, we estimate the quantity of land required for constructing county highways and remediating annual greenhouse gas emissions through forest carbon sequestration in the years 2001, 2011, and 2021. The results of our study, which focuses on Houghton County, Michigan, indicate that, despite a projected increase in average vehicle fuel efficiency, the ecological footprint of transportation will increase in future years because of projected increases in total annual vehicle kilometers of travel along the network. On the basis of these results, we argue that the ecological footprint is a viable technique for transportation and land-use planning applications.

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The rapid growth of urbanized regions since World War II has brought Americans not only great material wealth but also the degradation of natural ecosystems. Fortunately, many countries have begun to treat this problem seriously and are moving toward the models of sustainable development first articulated at the Rio Earth Summit of 1992 (Brady and Geets 1994). As defined by the United Nations World Commission on Environment and Development (WCED), sustainable development requires that the economic and social needs of current generations be met without sacrificing the ability of future generations to achieve an acceptable quality of life (WCED 1987).

An initial step in developing sustainable models of urban growth requires that the environmental impacts of current settlement patterns be fully established. To this end, the "ecological footprint" method has been proposed as a standard methodology for evaluating the direct environmental implications of alternative development models. Developed by Mathis Wackernagel and William Rees at the University of British Columbia, the ecological footprint measure quantifies the total land area required to support human settlement. As explained by its creators, "[e]cological footprint analysis is an accounting tool that enables us to estimate the resource consumption and waste assimilation requirements of a defined human population or economy in terms of a corresponding productive land area" (Wackernagel and Rees 1996, p. 9). More specifically, the ecological footprint of a population is calculated by determining how much land and water area are required to produce all the goods consumed and to assimilate all the wastes generated by that population (Rees 2000).

The principal advantage of the footprint measure for environmental impact analysis is that it adopts a physical variable—units of land area—as a common metric for comparing alternative models. In contrast to such nonphysical metrics as units of currency, the physical area required to support a community provides a resource-constrained means of quantifying impacts. Although monetary capital fluctuates from year to year and is (theoretically) unconstrained over time, natural capital in the form of physical land area is limited within the boundaries of a municipality, the borders of a country, or the dimensions of the planet. As a result, the ecological footprint measure provides a means of assessing the amount of a resource that is being used relative to the amount that is available. In short, the ecological footprint variable directly embodies the ecological concept of carrying capacity.

As a measure of carrying capacity, the ecological footprint provides an unambiguous standard for quantifying sustainability: sustainable communities are those for which the area of land consumed in the production of resources and assimilation of wastes is less than or equal to the total available land area. Yet, despite the clear advantage of this standard over other metrics of environmental performance, the ecological footprint approach has been criticized on two important grounds. First, the ecological footprint is limited in application to spatial dimensions for which detailed resource information is available. Often collected and maintained at the state or national level, many measures of footprint intensity, such as area of productive agricultural land or the quantity of energy consumed, may not be readily available at the level of the town, city, or county (Yount et al. 2000). The need for more-

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disaggregate levels of data can undermine the utility of this approach for land-use planning applications, which are generally conducted at the local scale. Second, the ecological footprint measure was conceived by its creators to provide a static "snapshot" of present conditions. As explained by Rees (2000), "Ecological footprinting is an ecological camera—each analysis provides a snapshot of a population's current demands on nature, a portrait of how things stand right now under prevailing technology and social values" (p. 373). The ecological footprint method, which lacks predictive value, has not proved useful for projecting the impacts of future development scenarios. This shortcoming in applying the approach has greatly limited the utility of the ecological footprint concept as a tool for evaluating alternative land-use planning scenarios and is a primary reason that the technique has not received broader attention within the planning literature.

In response to those two criticisms, this paper presents a methodology for integrating spatial analysis techniques with the ecological footprint approach to quantify the impacts of transportation networks in present and future time periods. Through using a geographic information system [as suggested by Moffatt 1996, 2000; Moffatt and Hanley (2001)], it is possible to quantify both the physical land area occupied by a roadway network, as well as the hypothetical land area required to sequester the carbon dioxide emitted through constructing, maintaining, and operating (vehicle usage) the transportation system. Following the presentation of our methodology, we will quantify the land area presently required to support the highway road system of a predominantly rural area in Michigan and then extrapolate these impacts to the years 2011 and 2021.

The results of this analysis, the first study to project a future ecological footprint, provide a basis for assessing the relative sustainability of alternative development futures within a single county. As such, this work develops a dynamic analytical tool that is applicable to local-scale land planning processes.

Research Background

A transportation network was selected as the focus of this study because of the significance of energy consumption for transportation and road-induced growth to future development and sustainability (Newman and Kenworthy 1999; Cervero 2003). As the leading edge for new development, large arterials play a central role in determining the pace and character of future growth and are a principal focus of local and regional transportation and land-use planning. In addition to the significance of road networks to planning policy, the future impacts of road networks can be reliably forecast with information on past trends in roadway usage. For this research, information on annual vehicle kilometers of travel and vehicle fleet characteristics is used to project the growth in vehicle travel and in carbon dioxide emissions over time.

Following the presentation of a methodology for quantifying the ecological footprint of a roadway network, we apply the methodology to a county-level highway network in Michigan. Houghton County, Michigan, was selected as the study region for this research because of the characteristics of the local transportation network and because of the availability of data on a number of travel characteristics. Located in Michigan's Upper Peninsula, Houghton County is approximately 2,590 square kilometers in area and has a population of 36,016 (U.S. Census Bureau 2002). Because the county is predominantly rural, the Houghton road network consists of a small number of principal arterials, thereby making the ecological footprint computation more simple than that for a complex road network. Although the Houghton County road network is modest in terms of lane kilometers, the Michigan Department of Transportation (MDOT) maintains an extensive database on regional travel flows throughout the state, collects annual traffic counts at numerous observation points throughout the county, and maintains data on vehicle fleet characteristics. This combination of network simplicity and data availability makes Houghton County an ideal site for this type of analysis.

As previously noted, the transportation footprint methodology quantifies two attributes of roadway networks. First, with the aid of a geographic information system (GIS), the total land area physically occupied by roadway paving is estimated. This "physical" footprint is easily derived with information about the number of lane kilometers of highway roads. Second, we must assess the amount of land that is required to remediate the energy waste produced through constructing, maintaining, and operating a roadway network—a component we term the "energy" footprint. Previous studies have employed one of three approaches for converting fossil energy into a corresponding land area: the ethanol approach (Wackernagel and Rees 1996), the CO_2 absorption approach (Wada 1994), and the biomass replacement approach (Serafy 1988). The CO_2 assimilation approach, which was adopted for this research, calculates the land area required to absorb or sequester the CO_2 emitted from burning fossil fuel. It is estimated that one hectare of forest can sequester annually the CO_2 generated by the consumption of 100 gigajoules of fossil fuel (Wada 1994). Because this approach results in the smallest footprint of fossil fuel consumption and because many reviewers believe that it will achieve the highest public acceptance (Wackernagel and Rees 1996), we have adopted this ratio for our analysis.

Overview of Methodology

The methodology developed to calculate the ecological footprint of transportation networks is presented as a chart in Fig. 1. As indicated by the figure, our approach consists of three principal steps: (1) estimating the physical footprint of the roadway network on the basis of the surface area of roadway paving; (2) estimating the energy footprint of the roadway network on the basis of the area of forest land required to sequester carbon emissions produced by network travel during one year; and (3) combining the land areas of the physical and energy footprints to derive an estimate of the total transportation footprint. To apply the methodology at the county or municipal level, information on average daily traffic counts, vehicle fleet composition, fuel efficiency rates by vehicle class, and roadway network design must be obtained from state departments of transportation and the U.S. Federal Highway Administration. In addition, local rates of carbon sequestration may be adjusted with information from state departments of natural resources or other government agencies charged with forest management.

In the first step in the methodology, Step 1 in Fig. 1, the physical footprint which is based on the physical dimensions of the roadway network is derived. Digital maps of the surface transportation network—which are available from a number of local, state, and federal agencies—can be analyzed to measure the width and length of street segments in the regional roadway system. By summing the area of all roadway segments in a study region, an estimate of the physical footprint of the street network may be derived.

In the second step of the methodology, show as Step 2 in Fig.

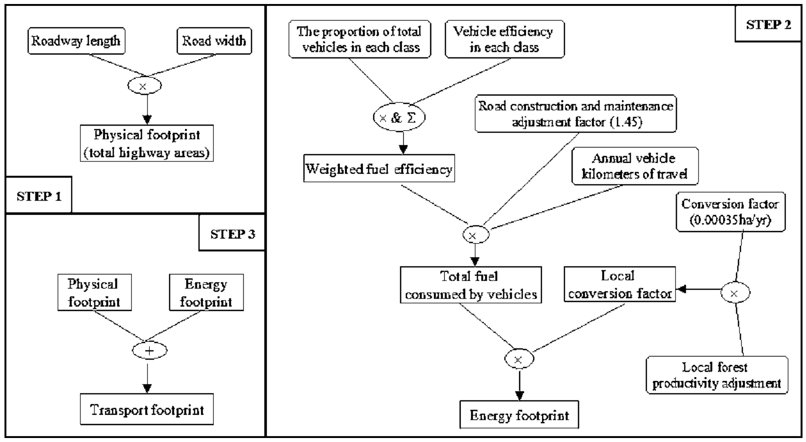

Fig. 1. Methodology for estimating the ecological footprint of vehicle travel

1, annual vehicle travel and vehicle fleet characteristics are employed to estimate the total quantity of fuel consumed in one year of travel along the network. In addition, the quantity of fuel consumed in constructing (allocated over the life of the network) and maintaining the roadway network is combined with that consumed in annual use to estimate the total quantity of fuel consumed per year of network operation. This estimate is multiplied by a carbon sequestration factor to estimate the area of forestland required to remediate the carbon dioxide emitted from each liter of fuel consumed in the operation of the transport network.

In the final step of the methodology, the physical and energy footprints are summed to derive the total transportation footprint, as indicated in Step 3 of Fig. 1. This estimate represents the total area of land required to physically support the transportation network and to sequester carbon dioxide emissions associated with the annual operation of the network. The derivation of the transportation footprint for present and past years provides a basis for projecting the ecological impacts of regional transport systems into future time periods.

As explored in the following discussion, the application of this transportation footprint methodology to a county-level highway network in Michigan provides a detailed illustration of how to employ this analytical framework to assess the sustainability of present and future surface transportation investments. Following the presentation of the Houghton County case study, the paper concludes with a discussion of the utility of the footprint approach to the field of transportation planning.

Case Study: Calculating Transportation Footprint in Houghton County, Michigan

As previously noted, Houghton County, Michigan, was selected as an ideal region for this analysis because of the availability of information on the highway network in a digital format, as well as the potential for significant growth in vehicle travel in the future. Before the footprint methodology can be applied, detailed information on roadway characteristics and annual vehicle flows must be obtained from state and federal planning agencies. We obtained information from the Michigan Department of Transportation on the dimensions and lane kilometers of the Houghton County highway system and vehicle traffic counts at 43 sites for the years 1996 through 2001. In addition, we obtained data on ownership by vehicle type within the county (e.g., number of cars, trucks, and buses) from the Michigan Department of State, as well as fuel efficiency information by vehicle class from the Federal Highway Administration (2001). On the basis of these data, we estimated the current and future size of the highway network footprint in Houghton County.

The first step in the methodology requires that the physical footprint of the Houghton County road network be estimated. The county highway system, depicted in Fig. 2, consists of approximately 195 kilometers of two-lane roads. Since the average width of a county highway is approximately 18 meters (including shoulders), the physical footprint of the network may be estimated through the following simple equation:

$$\text{Total highway area} = \text{roadway width } (18\text{ m}) * \text{roadway length } (195\text{ km})$$

The result of this equation indicates that the land surface area occupied by the Houghton County highway network is 356 hectares (3.56 square kilometers).

The next step in the methodology requires that we estimate the total area of forested land required to absorb the carbon dioxide produced through the construction, maintenance, and annual operation of the network. As previously noted, we term this component of the total network footprint the *energy footprint*. To calculate the energy footprint, we must first derive an estimate of the total fuel consumed in a given year of facility usage and then convert this figure to forest acreage by using a CO_2 conversion ratio. Annual vehicle CO_2 emissions are a product of the number of kilometers traveled per year and the fuel efficiency of the vehicle fleet. As a result, we must estimate annual vehicle kilometers of travel and average fuel consumption by vehicle class in Houghton County over a multiyear period. The steps in this process are detailed in the following sections.

Deriving Estimate of Annual Vehicle Kilometers of Travel

To monitor the annual volume of highway travel, the Michigan Department of Transportation has established an extensive network of traffic-survey stations throughout the state. For this study, we were able to obtain annual daily traffic counts collected at 43 survey stations located within or close to Houghton County for the years 1996 through 2001. As illustrated in Fig. 2, these traffic-survey stations are spatially distributed throughout the region and tend to be clustered within the urbanized portion of the county. The average daily traffic counts collected over a 24-hour period

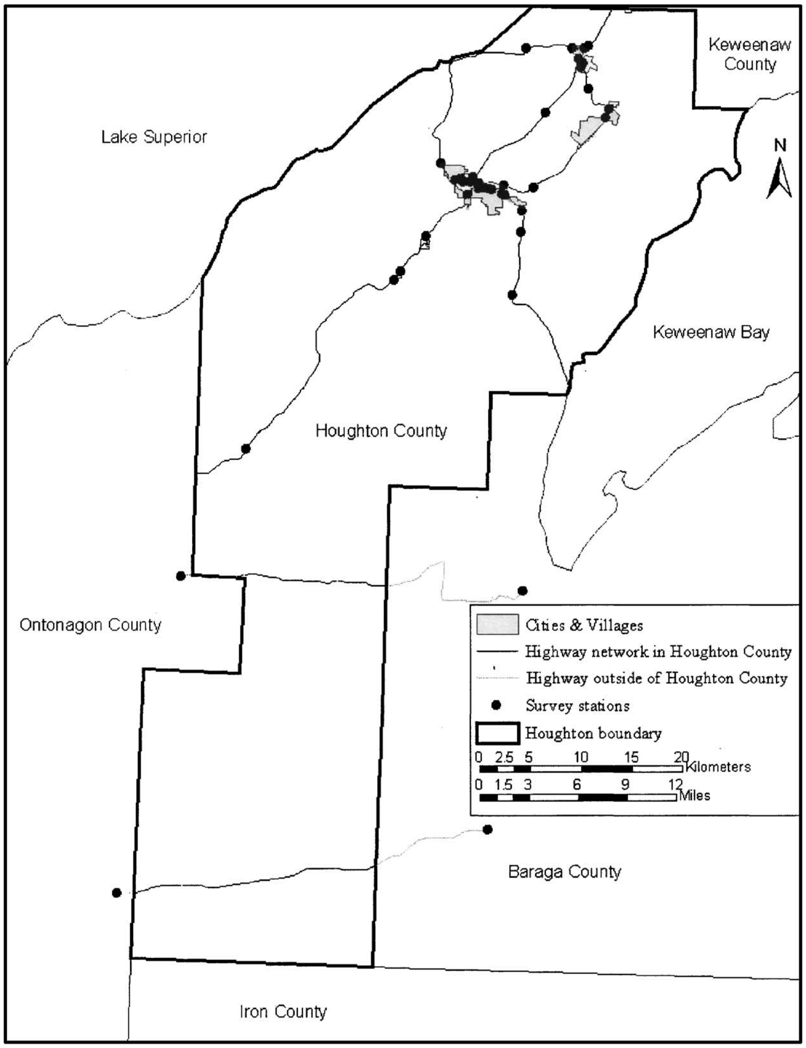

Fig. 2. Highway network and survey stations in Houghton County, Michigan [Data Source: Michigan Department of Natural Resources (DNR) Spatial Data Library, Michigan Department of Transportation, and Michigan Department of State]

can be multiplied by the length of the roadway between two survey stations and then by the number of days in a year to derive an estimate of total annual vehicle kilometers of travel along any segment of the highway network. After this estimate has been obtained, the vehicle travel distance is multiplied by an average fuel efficiency factor to yield an estimate of total fuel consumption and carbon dioxide emissions.

Estimating Vehicle Fleet Fuel Efficiency

The quantity of fuel consumed in a year of vehicle travel is a product of the total travel distance and the consumption of fuel per kilometer of travel. Because different classes of vehicles consume fuel at different rates, we must determine the relative proportions of different vehicle types traveling within a given year along the network. We were able to obtain from the Michigan Office of Planning and Integration the number of vehicles in the six vehicle classes for the years 1999, 2000, and 2001. The six vehicle classes, as shown in Table 1, include passenger cars, other 2-axle 4-tire vehicles, single-unit 2-axle 6-tire or more trucks, combination trucks (i.e., tractor-trailer trucks), motorcycles, and buses. Because no fleet data are available for 1996, 1997, or 1998, years for which we were able to obtain average daily traffic

Table 1. Vehicle Class Composition

	Number of vehicles						
Vehicle class	1996	1997	1998	1999	2000	2001	R^2
Passenger cars	15,934	16,149	16,363	16,556	16,836	16,985	0.9699
Motorcycles	548	558	568	569	490	708	0.3965[a]
Other 2-axle 4-tire vehicles	6,419	6,603	6,786	6,981	7,130	7,348	0.9884
Single-unit 2-axle 6-tire or more trucks	136	138	140	136	167	133	0.0063[a]
Combination trucks	597	608	619	701	564	657	0.0989[a]
Buses	16	17	17	34	8	10	0.6879[a]
Total after projection	23,650	24,073	24,493	24,977	25,195	25,841	

Note: Data source: Office of Planning and Integration, Michigan Department of State.

[a] R^2 values less than 0.75 were deemed to be unreliable in estimating fleet composition for the years 1996–1998.

Table 2. Proportion of Fleet in Each Vehicle Class by Year

Vehicle class	Number of vehicles as proportion of total 1996	1997	1998	1999	2000	2001
Passenger cars	0.6737	0.6708	0.6681	0.6628	0.6682	0.6573
Motorcycles	0.0232	0.0232	0.0232	0.0228	0.0194	0.0274
Other 2-axle 4-tire vehicles	0.2714	0.2743	0.2771	0.2795	0.2830	0.2844
Single-unit 2-axle 6-tire or more trucks	0.0058	0.0057	0.0057	0.0054	0.0066	0.0051
Combination trucks	0.0252	0.0253	0.0253	0.0281	0.0224	0.0254
Buses	0.0007	0.0007	0.0007	0.0014	0.0003	0.0004
Total after projection	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Note: Data source: Office of Planning and Integration, Michigan Department of State.

counts along the network, a linear regression model was developed to back-project vehicle class composition in Houghton County for these first three years of the analysis.

As listed in the final column of Table 1, the R^2 values for four of the six vehicle classes—single-unit 2-axle 6-tire or more trucks, combination trucks, buses, and motorcycles—were found to be low, indicating that the estimates may not be reliable. In light of this finding, we decided to derive estimates for these vehicle classes on the basis of their average proportional representation in the years 1999–2001, years for which observed data are available. The resulting number of vehicles by class and year as a percentage of the fleet total is presented in Table 2.

Data on fuel efficiency by vehicle class and year were obtained from the U.S. Federal Highway Administration. These fuel efficiency statistics, presented in Table 3, were used to derive a weighted average of fuel consumption per kilometer of travel in Houghton County. Specifically, the per kilometer fuel consumption figure for each vehicle class was multiplied by the fleet-composition percentage values reported in Table 2. These values were then summed to derive an estimate of the average fuel consumed per kilometer of travel by the Houghton County vehicle fleet. The results of this computation for each year are presented in the final row of Table 3.

Computing the Energy Footprint

After we developed a routine to estimate the total liters of fuel consumed in a year of travel along Houghton County highways, the final step in the energy-footprint estimation process is to calculate the quantity of carbon dioxide emitted and the acreage of forest required to sequester these greenhouse gas emissions. As previously noted, data on forest productivity suggest that one hectare of forest can annually absorb approximately 1.8 tons of carbon, which is generated by the consumption of 100 gigajoules of fossil fuel (Wada 1994). Research indicates that each liter of gasoline produces about 0.033 gigajoules of energy (Statistics Canada 1996) and that each liter of diesel produces about 0.039 gigajoules (Girouard et al. 1999) or 0.036 gigajoules (Skatteudvalg 1999). Since these estimates are close in magnitude, we use 0.035 gigajoules per liter for both gasoline and diesel. Therefore, the energy footprint for one liter of gasoline or diesel may be estimated with the following equation:

$$\frac{1(\mathrm{L}) * 0.035\ \mathrm{GJ/L}}{100\ \mathrm{GJ/ha/year}} = 0.00035\ \mathrm{ha/year}$$

On the basis of this equation, over the period of one year, an average of 0.0035 hectare of forested land is required to sequester the carbon dioxide emitted from the burning of one liter of fuel.

Road Construction and Maintenance Adjustment

In addition to fuel consumed through vehicle travel along a network, energy consumed in the process of network construction and annual road maintenance must also be reflected in the total transportation network footprint. Wackernagel and Rees (1996) estimated that the indirect carbon emissions for road construction and maintenance are equivalent to 45% of the total annual fuel consumed for vehicle travel. As indicated in Fig. 1, this quantity can then be multiplied by the estimate of fuel consumption for annual vehicle travel to derive the total annual consumption of fuel for network construction, maintenance, and operation. Because of the long winter and heavy snow in Houghton County, a greater than average amount of energy consumption for road maintenance is needed. Because a road maintenance factor for Houghton County has not been calculated, using the average ratio of 45% for this case probably underestimates the energy footprint.

Local Forest Productivity Adjustment

A final step in calculating the energy footprint requires that the forest sequestration rate be adjusted to account for local conditions favorable to carbon uptake. Houghton County forests—which are endowed with a unique mix of tree species, density, and age distribution—can be expected to achieve a higher rate of carbon sequestration than the average forest. According to Kurt Pregitzer of Michigan Technological University, a figure of 2.0 metric tons of carbon sequestration per hectare, rather than 1.8 tons per hectare, is reasonable and conservative for Houghton County (personal communication in spring 2002). This higher sequestration productivity translates into a smaller footprint per hectare of forest. Therefore, we assume that 0.9 hectare of Houghton County forest land will be required to sequester the carbon dioxide emitted from the consumption of 100 gigajoules of energy. The footprint of one liter of gasoline/diesel in Houghton County then becomes:

$$0.00035\ \mathrm{ha/year} * 1.45 * 90\ \% = 0.00045675\ \mathrm{ha/year}$$

We use this final conversion factor of 0.00045675 ha/year in calculating Houghton County's highway transportation footprint for the years 1996 through 2001.

Table 3. Fuel Efficiency in Liters per Kilometer

Vehicle class	1996	1997	1998	1999	2000	2001
Passenger car	0.1115	0.1094	0.1098	0.1098	0.1070	0.1063
Motorcycle	0.0470	0.0470	0.0470	0.0470	0.0470	0.0470
Other 2-axle 4-tire vehicle	0.1367	0.1367	0.1376	0.1383	0.1343	0.1336
Single-unit 2-axle 6-tire or more truck	0.3460	0.3361	0.3361	0.3135	0.3178	0.3178
Combination truck	0.3987	0.3855	0.3855	0.4356	0.4439	0.4439
Bus	0.3564	0.3512	0.3512	0.3512	0.3460	0.3408
Average fleet fuel efficiency	0.1254	0.1240	0.1244	0.1270	0.1296	0.1223

Note: Data source: Federal Highway Administration (2001).

Table 4. Transportation Network Footprint Statistics for 1996–2001

	Total annual vehicle travel (kilometers)	Average fleet fuel efficiency (liters per kilometer)	Conversion factor (hectares of forest per liter)	Energy footprint (hectares)	Physical footprint (hectares)	Total footprint (hectares)
1996	245,247,478	0.125	0.00045675	14,002	356	14,358
1997	247,277,903	0.124	0.00045675	14,005	356	14,361
1998	256,606,388	0.124	0.00045675	14,533	356	14,889
1999	269,187,059	0.127	0.00045675	15,615	356	15,971
2000	269,880,668	0.129	0.00045675	15,902	356	16,258
2001	288,884,626	0.122	0.00045675	16,098	356	16,454

Measuring Transportation Footprint from 1996 through 2001

With the aid of the preceding calculations, it is possible to measure the transportation network footprint for any year for which data are available on network traffic volumes, vehicle types, and vehicle fuel efficiencies. In this section of the paper, we present the results of the Houghton County analysis for 1996 through 2001; and in the following section, we use these results to project the transportation footprint to the years 2011 and 2021.

As previously described, the transportation network footprint may be estimated by summing the area of the physical and energy footprints. The physical footprint, defined as the paved area of the highway network, was calculated to be 3.56 square kilometers—a figure that does not change unless the network is expanded or otherwise modified. For the purposes of this analysis, we assume that the network structure remains unchanged over time.

The energy footprint is a product of the total number of liters consumed in a year of travel along the network (including fuel consumption for construction and maintenance) and the area of forested land required to sequester the carbon dioxide produced by this vehicle travel. The number of liters of fuel consumed is a product of the number of kilometers traveled by vehicles in each of the six vehicle classes and the fuel efficiency of each vehicle class. On the basis of the data presented in Tables 2 and 3, we calculated that the average liters consumed per mile of travel ranged from a high of 0.1296 in 2000 to a low of 0.1223 in 2001.

The total number of kilometers traveled along any segment of roadway during the year can be estimated with the vehicle traffic-count data provided by the Michigan Department of Transportation. To calculate this value, we simply multiply the total number of vehicles traveling along a network segment times the segment length in kilometers and multiply the result by 365, the number of days in a year. The result of this equation yields the cumulative number of kilometers traveled along each traffic survey segment depicted in Fig. 2. Summing these values across each segment in the highway network yields an estimate of the total number of highway kilometers traveled in a given year.

After deriving the total number of kilometers traveled each year and the average fleet fuel consumption per kilometer of travel, we can easily calculate the number of liters consumed in a year of travel along the Houghton County highway network as the product of these two values. We then multiply this figure by 1.45 to account for the fuel consumed annually in constructing and maintaining the facility. As a final step, the total number of liters consumed in annual operation of the highway network is multiplied by the number of hectares of forestland required to sequester the carbon emitted from the burning of one liter of fuel. As previously discussed, this conversion factor, accounting for conditions unique to Houghton County, was estimated to be 0.00045675. With this information, the total network footprint (FP) in any year of travel may be calculated with the following equation:

$$\text{Network footprint} = \text{energy FP } (0.00045675 * \text{liters consumed}) + \text{physical FP } (3.56 \text{ square kilometers})$$

As detailed in Table 4, the results of this calculation process for each of the study years shows that the ecological impact of vehicle travel in Houghton County decreased slightly between 1996 and 1997 and then increased steadily through 2001. Since the physical footprint and carbon sequestration rate remained constant during this period, the growth in the region's transportation footprint can be attributed to a significant growth in annual kilometers of travel coupled with modest fluctuations in fuel efficiency. In 2001, the total transportation footprint is equivalent to 6% of the county's total land area and is about 45 times greater than the area of the physical footprint alone. In the absence of capacity improvements to the network over time, the energy footprint can be expected to constitute a growing percentage of the total network footprint as facility usage grows.

Mapping the Transportation Footprint

The utility of footprint analysis lies not only in the development of a capacity-limited measure of environmental impact but also in the ability to spatially display varying degrees of environmental impact across a study region. In the context of roadway impacts, we can map the transportation footprint through designating "buffer zones" along the highway corridors in Houghton County by using a GIS. Buffer zones are linear features that spatially delineate a zone of protection or impact along a linear cartographic feature, such as a roadway or stream. In this analysis, we use buffer zones to illustrate the variable size of the transportation footprint along the highway network.

The first step in creating the highway buffer zones is to derive an equation for estimating the width of the buffer zone for any highway segment. Because traffic volumes are assumed to remain fixed in proximity to MDOT traffic survey stations (Fig 2), a segment of highway is delineated as the stretch of roadway between the midpoints of two traffic survey stations. Because traffic volume varies from segment to segment, buffer width may be expected to vary as well.

The buffer width for any segment of the highway network can be derived by summing the physical and energy footprints (in units of square meters) for the segment and dividing by the segment's length in meters. The physical footprint for any segment of highway is easily computed by multiplying the segment's length in meters times the fixed roadway width of 18 meters. As detailed in the preceding sections, the energy footprint of a single segment

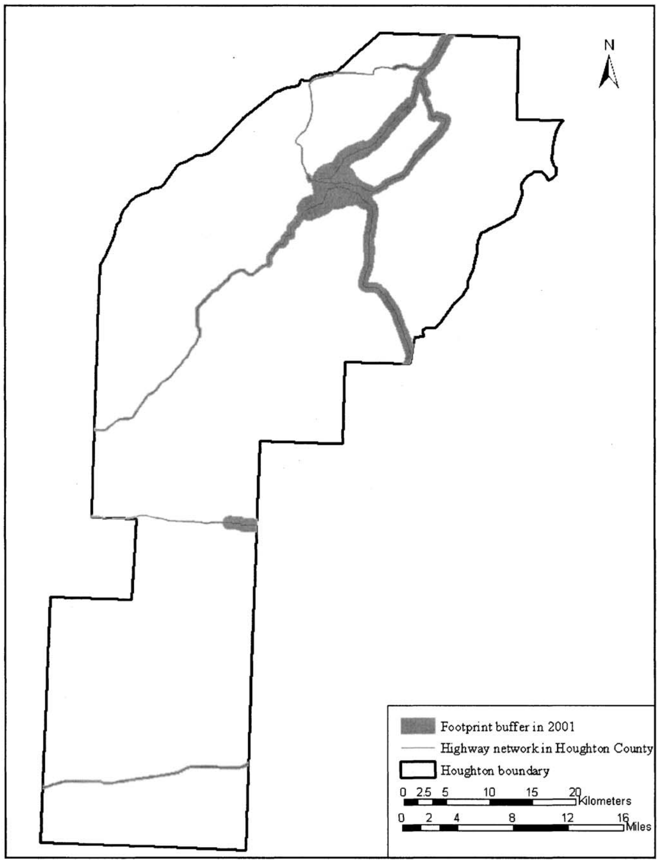

Fig. 3. Footprint buffer in Houghton County, Michigan, 2001 (Data Source: Michigan DNR Spatial Data Library, Michigan Department of Transportation, and Michigan Department of State)

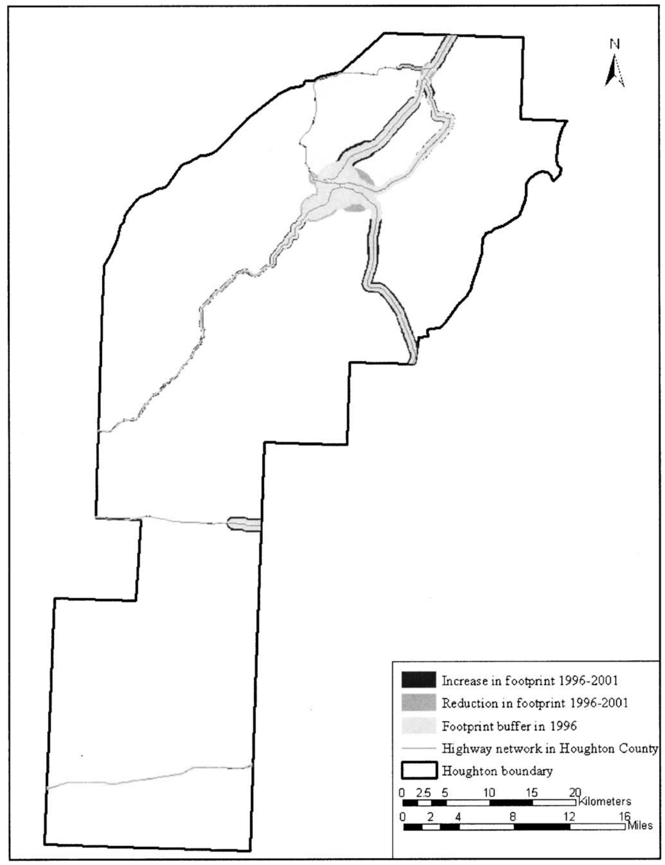

Fig. 4. Footprint change in Houghton County, Michigan, 1996–2001 (Data Source: Michigan DNR Spatial Data Library, Michigan Department of Transportation, and Michigan Department of State)

of roadway is a product of the total number of vehicle kilometers in a year of travel along the segment (i.e., vehicle traffic count times the segment length times 365), the average fleet fuel consumption per kilometer of travel, and the area of land required to sequester the carbon dioxide emitted from this travel. After the physical and energy footprints for an individual roadway segment have been estimated, the width of the buffer zone along that segment of road can be derived through the following simple computation:

$$\text{Buffer width (m)} = \frac{\text{physical footprint (m}^2) + \text{energy footprint (m}^2)}{\text{Length of roadway segment (m)}}$$

The results of this buffer-width estimation process for 2001, the most recent year for which complete data are available, are presented in Fig. 3. As expected, the greatest areas of impact are located in the central business district, where the highest levels of vehicle use are found. In the less-developed regions of the county, to the south and west, vehicle traffic counts are lower; and hence, the footprint buffer widths are more narrow.

Another means of visualizing the spatial magnitude of transportation impacts in Houghton County is through developing of a "net" buffer zone designed to depict the growth in the transportation footprint over time. Fig. 4 shows the growth in the transportation buffer between 1996 and 2001. As illustrated in this figure, although the greatest impact zone is located in the central business district, the region's growth in travel impacts tends to be located in the more rural areas of the county. Interestingly, a few highway segments in the urbanized regions of the county were found to have a negative net buffer, indicating that the size of the segment footprint was lower in 2001 than in 1996. Since the physical footprint is assumed to remain unchanged from year to year, the variation in footprint size between 1996 and 2001 is a product of changes in vehicle kilometers of travel and average fleet fuel consumption. A negative net buffer can result any time that the rate of reduction in fuel consumption outpaces the rate of increase in vehicle travel or when vehicle travel decreases over time. For each of the highway segments depicted as having a negative footprint buffer in Fig. 4, the annual kilometers of travel along the segment were found to be lower in 2001 than in 1996. This observed decline in vehicle travel in the central business district may be indicative of decentralizing residential and commercial land uses, drawing traffic toward the lower-density regions of the county.

Projecting the Transportation Footprint

The ability to project ecological footprints into the future provides an empirical basis to assess how future development scenarios will conform to a region's available carrying capacity. The ecological footprint concept, which has been employed to date only in evaluating current development patterns, has provided a descriptive rather than an explanatory tool for understanding how various development patterns influence environmental quality. In

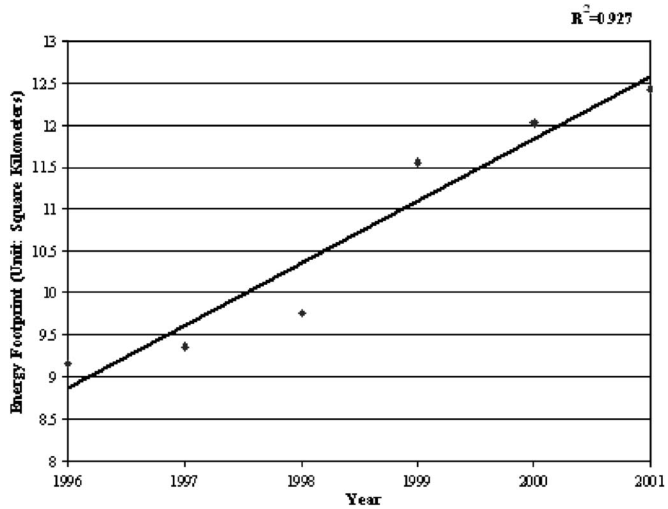

Fig. 5. Energy footprint for one US-41 segment in northern Houghton County, Michigan

this sense, the method provides a basis to put into operation the concept of sustainability only in a past or present period. To be useful in formulating long-range transportation and land-use plans, the footprint methodology must be capable of forecasting land impacts resulting from alternative policy options governing land development and travel behavior. In this section, we develop a series of linear regression models to extrapolate future levels of the transportation network footprint on the basis of past trends.

The most direct means of forecasting a future transportation footprint is by using vehicle travel and fuel consumption projections for future years. Since no such data exist for our Houghton County case study, we developed a simple linear regression model to project past trends in footprint development 10 and 20 years into the future. Specifically, we fit a linear model to the six years of data that exist for each of the 43 highway survey segments to extrapolate this trend to the years 2011 and 2021, which are 10 and 20 years beyond 2001, the most recent year for which full data are available. The sum of these extrapolated segment footprints is equivalent to the total network footprint in future time periods.

Fig. 5 illustrates the simple trend extrapolation process for a section of highway located in Houghton County's central business district. For the approximately 6 km highway segment, the energy footprint value is plotted for each year of data. A regression line can then be fitted to these data with the following standard model, in which the dependent variable (Y) is the segment footprint value and the independent variable (X) is the year of data:

$$Y = b_0 + b_1 X$$

By using a GIS software package, a separate linear regression model was developed for each of the 43 survey segments and footprint values for the years 2011 and 2021 were derived. To gauge the overall predictive strength of this modeling process, a weighted average adjusted R^2 of 0.54 was computed. In calculating this statistic, each individual R^2 value was multiplied by the ratio of the individual highway segment length to the total length of the highway network and then summed. As described in the preceeding section, these segment footprint values can then be added to the physical footprint value, which is assumed to remain fixed over time, to develop a transportation buffer footprint map for each of the two future time periods. The results of this process are illustrated in Figs. 6 and 7.

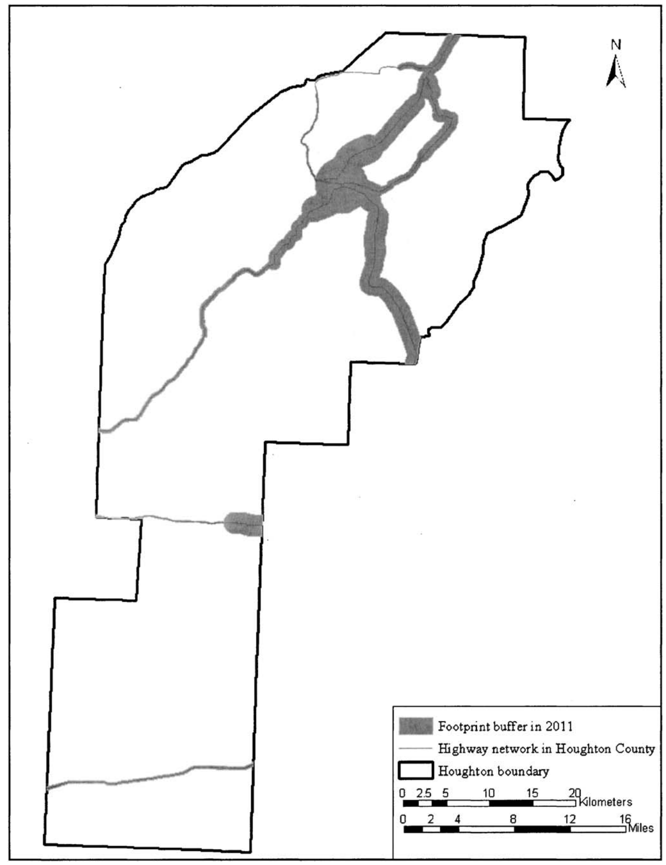

Fig. 6. Footprint buffer in Houghton County, Michigan, 2011 (Data Source: Michigan DNR Spatial Data Library, Michigan Department of Transportation, and Michigan Department of State)

The total network footprint for the year 2011 was found to be 217 km^2 and the total network footprint for 2021 was found to be 269 km^2. On the basis of the rates of growth in network vehicle travel and the relatively modest rates of increase in vehicle fuel efficiency from 1996 to 2001, the network footprint may be expected to grow steadily 10 and 20 years into the future. If current trends continue, the 2021 network footprint will be 63% larger than the 2001 network footprint and will require 10% of the land in Houghton County to support vehicle travel. In the absence of significant reductions in vehicle emissions over the next 20 years, the transportation sector will rival other critical land-use sectors, such as housing and agriculture, for available carrying capacity by 2021. In combination with these other sectors, the total ecological footprint for Houghton County may soon exceed the available land area, placing the county into a state of regional ecosystem "overshoot."

Fig. 8 presents the footprint differential between 2001 and 2021. As indicated by the large buffer widths found to the north and southeast of the central business district, much of the growth in transportation impacts is projected to occur outside the urban districts, indicating the need for congestion mitigation both inside and outside of the urban zones. A few highway segments are projected to experience a slight reduction in footprint size, similar to that shown in Fig. 4, over the 20-year period. Interestingly, a number of segments found to have a negative differential between 1996 and 2001 (Fig. 4) exhibit a positive differential between

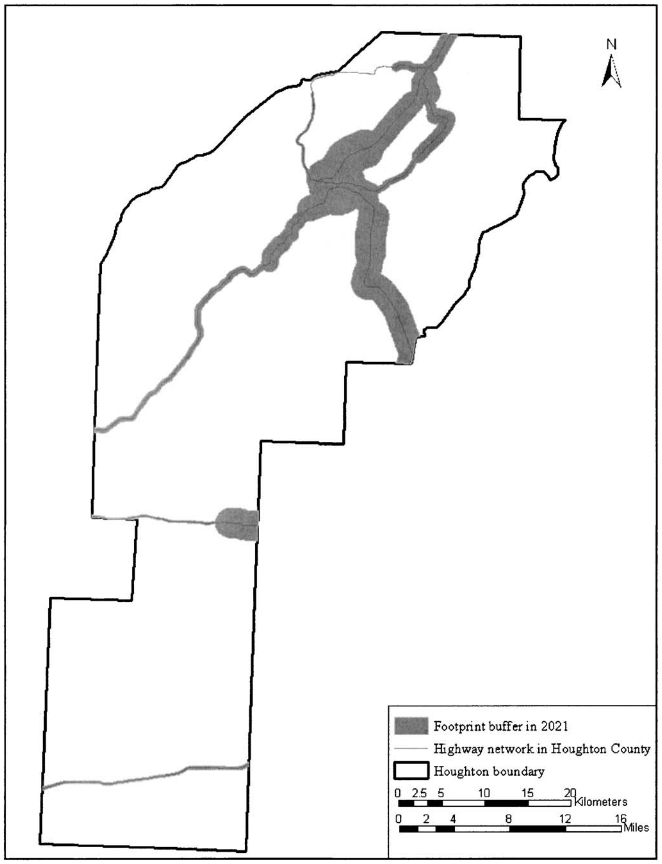

Fig. 7. Footprint buffer in Houghton County, Michigan, 2021 (Data Source: Michigan DNR Spatial Data Library, Michigan Department of Transportation, and Michigan Department of State)

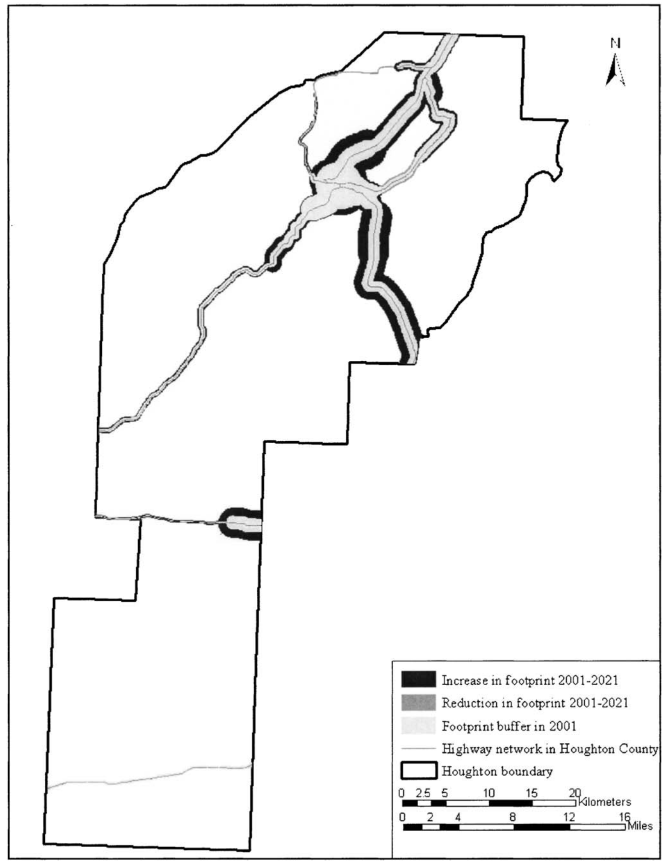

Fig. 8. Footprint change in Houghton County, Michigan, 2001–2021 (Data Source: Michigan DNR Spatial Data Library, Michigan Department of Transportation, and Michigan Department of State)

2001 and 2021. This outcome can be attributed to the use of a linear model, through which a positive trend in footprint growth may be found to result despite a negative differential between the endpoint years of 1996 and 2001. In each case, a straight-line model was fitted to an approximately U-shaped distribution of data, resulting in a slight positive or negative trend between roughly equivalent values in 1996 and 2001. As subsequently discussed, using a nonlinear model would likely yield greater predictive power for segment footprint values characterized by such nonlinear distributions.

Conclusions

This research advances the field of transportation planning in a number of respects. First, it develops a footprint methodology for quantifying the impacts of transportation investments at a spatial scale that is compatible with local planning policy. To most directly influence the scale and pattern of land development, the ecological footprint methodology—previously conducted only at the aggregate scales of states, regions, and countries—must be applied at a scale consistent with the land-use planning process of counties and municipalities, since they are the units of government typically vested with jurisdiction over land-use decisions. Performing a footprint analysis for a county-level highway road system with readily available data demonstrates how this technique can be incorporated into the established land use and transportation planning process.

Second, this work develops a framework for projecting the future land requirements needed to sustain a county-level transportation system in response to ongoing trends in annual vehicle kilometers of travel and average fleet fuel efficiency. In addition to assessing the environmental impacts of current development patterns, there is a critical need to model the implications of alternative development futures. This work combines footprint analysis with GIS and simple linear regression to forecast the future land requirements of a transportation network, assuming a business-as-usual scenario.

Although the utility of this approach for this field of planning is clear, a number of limitations should be noted in interpreting our findings. First, and most significantly, the accuracy of the analysis is constrained by data availability. Detailed information on vehicle fleet characteristics for the county is only available from 1999, so estimates must be used for previous years. In addition, the availability of daily traffic counts for only a single day each year may obscure seasonal variation in vehicle travel. In general, the reliability of the methodology's estimates will be greatest in regions where detailed and regularly compiled information on the regional transportation system is available.

A second important limitation of our analysis is the use of a straight-line model in projecting future network impacts. Although vehicle travel tended to increase between 1996 and 2001 and per kilometer fuel consumption decreased, these changes may not conform to a straight-line model in all cases. This observation is supported by the only moderately strong average R^2 value (0.54) computed for the linear models. In light of this finding, future work will examine the predictive strength of both linear and nonlinear models. With increasing data availability, future footprint analyses will also be improved with more successive years of impact data.

A final issue to be addressed in future work is the relative contribution of alternative land-use types and development scenarios to the total regional footprint. This study, which focused exclusively on the highway network footprint, did not seek to address the influence of other important land-use classes, such as residential, commercial, and industrial development. Through an analysis of public-land parcel records across many land-use types, a more complete accounting of the region's present and future ecological footprint may be derived. Also important in this respect is an assessment of alternative development scenarios. A key benefit of projecting regional footprints is the potential to quantify the relative sustainability of competing development proposals. Although this initial study sought only to extrapolate recent trends in highway use into future time periods, alternative assumptions pertaining to expansions of the road network, vehicle travel patterns, and transport technologies consistent with regional master plans could be incorporated into the methodology outlined herein. We believe that this final adaptation of the footprint methodology will prove most effective in incorporating the notions of sustainability and carrying capacity into the local and regional planning process.

Despite these limitations, the results of our case study analysis yield a number of important insights for applying the footprint concept to transportation networks. Our findings suggest that less than 0.5% of Houghton County's total land area was needed to support the physical footprint in 2001, while another 6% was needed to absorb the emitted carbon dioxide. The size of the total footprint is projected to increase to 10% by 2021. The disproportionate impact of carbon emissions on the transportation footprint highlights the significance of the footprint metric to future transportation planning. Presently undervalued in economic terms, the global ecological impacts of local transportation systems remain largely unaccounted for in the conventional transportation planning process. As a result, municipal and county-level governments are more likely to underestimate the long-term economic and environmental benefits of less energy-intensive modes of transport, such as mass transit and pedestrian modes of travel. The adoption of a footprint metric for transportation project evaluation would likely hold significant implications for the nature of future investments in surface transportation systems.

A second significant insight yielded by this analysis concerns the regional programming of congestion management strategies. As illustrated by the series of footprint buffer maps presented in Figs. 3–8, the most significant impacts in the present period are localized in the central business district. Over time, however, growth in the system's footprint appears to be increasing most rapidly outside the urbanized districts in the county, indicating the need for congestion mitigation measures in urban and less developed regions of the study area. These results illustrate the significance of a time-series approach to footprint analysis, in that changes in the footprint over time can suggest important directions for local planning policies. By contrast, the standard "snapshot" approach to footprint modeling yields few insights for planning over the long term.

In closing, the derivation of a current and future transportation footprint provides an important analytical tool for regional land use and transportation planning. As noted elsewhere, the ecological footprint concept has proven useful in conveying the significance of regional carrying capacity to stakeholders in the planning process. By reducing the various impacts of transportation to a single metric of land area, the transportation network footprint can be mapped and visually evaluated against the spatial requirements of other land-use sectors and against the total available land area. Most important, in accounting for a broader range of environmental impacts than generally considered, such as the land area required to sequester greenhouse gas emissions from the transportation sector, the ecological footprint measure encourages communities to manage growth long before a region is fully developed. The ability to measure and project transportation footprints will enhance the ability of land use and transportation planners to protect regional environmental resources and in so doing, move us further along the road to more sustainable patterns of development.

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