Energy Policy 38 (2010) 4880–4887

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Impacts of urban form on future US passenger-vehicle greenhouse gas emissions

Steve Hankey, Julian D. Marshall *

Department of Civil Engineering, University of Minnesota, 500 Pillsbury Drive SE, Minneapolis, MN 55455, United States

ARTICLE INFO

Article history:
Received 13 February 2009
Accepted 14 July 2009
Available online 21 August 2009

Keywords:
Smart growth
City design
Environmental planning

ABSTRACT

Urban form – for example, sprawl versus infill development – impacts people's daily travel patterns and annual vehicle-kilometers traveled (VKT). This paper explores how urban form impacts greenhouse gas (GHG) emissions from passenger-vehicles, the largest source of urban transportation GHG emissions. Our research uses a recently published urban scaling rule to develop six scenarios for high- and low-sprawl US urban growth. We develop and apply a Monte Carlo approach that describes ensemble statistics for several dozen urban areas rather than forecasting changes in individual urban areas. Then, employing three vehicle- and fuel-technology scenarios, we estimate total passenger VKT and resulting GHG emissions for US urban areas. Our results indicate that comprehensive compact development could reduce US 2000–2020 cumulative emissions by up to 3.2 $GtCO_2e$ (15–20% of projected cumulative emissions). In general, vehicle GHG mitigation may involve three types of approaches: more-efficient vehicles, lower-GHG fuels, and reduced VKT. Our analyses suggest that all three categories must be evaluated; otherwise, improvements in one or two areas (e.g., vehicle fuel economy, fuel carbon content) can be offset by backsliding in a third area (e.g., VKT growth).

1. Introduction

Transportation accounts for 34% and 13%, respectively, of US and global anthropogenic greenhouse gas (GHG) emissions (EIA, 2008b; IPCC, 2007). Three options for reducing transportation emissions are (1) low-carbon fuels or other energy carriers (e.g., electricity), which reduce the life cycle emissions per amount of energy, (2) more-efficient vehicles, which reduce energy consumption per vehicle-km traveled (VKT), and (3) VKT reductions, through options such as mass transit, energy-efficient urban form, improved logistics, demand-side management, and non-motorized travel such as walking and biking. Here, we focus on the third approach, recognizing that a comprehensive solution will involve all three options.

Urban form and neighborhood design play a role in determining mode choice and travel distance (Cervero and Radisch, 1996; Cervero, 2002). For example, population density (PD), land use and mass transit are causally related to per capita passenger-vehicle travel (Handy et al., 2005). Automobile dependence and transportation energy consumption per capita are greater for low-density suburban neighborhoods than for compact neighborhoods (Kenworthy and Laube, 1996; Vandeweghe and Kennedy, 2007). As a result, GHG emissions per household differ by city design, type and geographic location (Ewing and Rong, 2008; Glaeser and Kahn, 2008). Given the long history of scholarship on land use and transportation, we do not provide a detailed review here and instead point readers to excellent reviews elsewhere (e.g., Anderson et al., 1996; Crane, 2000; Ewing and Cervero, 2001; Handy, 1996).

US cities have experienced increasing amounts of car-dependent, sprawl-type development (i.e., leapfrog, low-density expansion) leading to debates on the benefits and costs of urban growth strategies (Burchell et al., 2002). Relationships between the built environment and travel behavior have typically been studied on a neighborhood or regional (metropolitan) scale (Donoso et al., 2006; Ewing et al., 2007; Hunt, 2003; Rodier et al., 2002). Groups of cities (and their GHG emissions) have been studied using cross-sectional data (Bento et al., 2004) or for the purpose of predicting metropolitan level travel activity (Cameron et al., 2003). Previous work has employed the ASIF (emissions are the product of activity [A], modal share [S], modal energy intensity [I], and fuel mix [F]) and IPAT (environmental impact [I] is the product of population [P], affluence [A], and technology [T]) frameworks to model travel behavior (Grimes-Casey et al., 2009; Schipper et al., 2000; Zegras, 2007) and concluded that activity (e.g., VKT per capita) is an important factor in transportation emissions. Recent modeling of the US Midwest suggests that compact growth could achieve long-term emission reductions equivalent to the hybridization of the light duty vehicle fleet (Stone et al., 2009).

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* Corresponding author. Tel.: +1 612 625 2397; fax: +1 612 626 7750.
E-mail address: julian@umn.edu (J.D. Marshall).

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doi:10.1016/j.enpol.2009.07.005

This study (1) examines urban growth patterns for 142 US cities during 1950–2000 and predicts 6 plausible urban expansion scenarios for 2000–2020 and (2) estimates the GHG emissions from passenger vehicles in these urban areas for each scenario. Our study expands on previous work in several ways. First, we explore urban expansion and GHG emissions for a linked set of urban areas that conserve total population growth (e.g., if one city constrains population growth then the growth occurs in other cities). Second, we maintain consistency with a published urban growth scaling rule (Marshall, 2007). Specifically, values among urban areas for the parameter linear population density (LPD; described below) are required to match a given mathematical distribution. Third, we use a Monte Carlo approach to predict urban growth that focuses on statistical distributions of urban parameters rather than relying on accurate prediction of which cities will grow and by how much. Given the difficulties in accurately forecasting growth rates and the locations for land-use shifts in specific cities (Ewing and Cervero, 2001), we believe that our approach provides a novel and useful method for exploring trends in urban growth and their environmental impacts. Fourth, we incorporate a range of plausible scenarios for technological innovation (vehicles; fuels), thereby shedding light on the relative potential GHG impact of changes in technology versus in urban form. A primary goal of this article is to develop a new Monte Carlo-based method for predicting multi-city urban growth and its environmental impacts, and in doing so to explore one application of urban growth theory.

2. Methods

2.1. Urban growth scenarios

We analyzed the 142 cities defined by the US Census as an Urban Area in 1950. This subset of cities represents over half (56%) of the year-2000 US population and includes 36 of the 37 cities with a year-2000 population over 1 million (Las Vegas became a Census Urban Area in 1960). Six urban growth scenarios are evaluated here: three scenarios that replicate historic decadal growth rates (S1, S2, S3) and three bounding scenarios in which urban growth deviates from historic patterns (Complete Infill, Constant Density, Suburban Nation). All six scenarios are shown in Table 1. A list of cities evaluated, with US Census year-2000 populations and land areas, is in Appendix 1.

As described next, our growth scenarios involve three steps: (1) generate Monte Carlo statistical distributions (1000–10,000 distributions per scenario) for four urban-form parameters for each city (population, area, population density, linear population density), representing year-2020 conditions, (2) remove distributions that do not conform to the urban scaling rule, and (3) based on population and population density, predict total VKT. Technology scenarios are then employed to estimate passenger-vehicle greenhouse gas emissions. Emissions from other modes – for example, buses, trains, and airplanes – are excluded from this analysis.

Our Monte Carlo method accounts for the variance in all three input parameters used to calculate year-2020 scenarios: (1) the population distribution, (2) the population/area correlation, and (3) the VKT/population-density correlation. Each Monte Carlo scenario introduces this variance by creating a distribution of values for each parameter based on historic observations. Scenarios S1 and S2 required 1000 iterations to satisfy the LPD constraint while S3 required 10,000 iterations (see below). For each iteration, means and coefficients of variability for historic population distributions (1950–2000) were extrapolated to predict the year-2020 population distribution. Similarly, regression parameters (slope) for the population-area correlation were allowed to vary randomly, consistent with uncertainty in historic regressions. Lastly, the VKT for each future city was randomly adjusted using the average deviation in the VKT/population-density correlation (12.5%) as a basis. These inputs are discussed in further detail below; Fig. 1 provides a flowchart of the Monte Carlo routine.

The US Census predicts that the US population will increase 18% from 2000 to 2020 (US Census, 2000); applying this growth rate to our cities results in a total year-2020 population of 180 million. Here and elsewhere, we modeled two groups of cities separately: (1) most cities (year-2000 population less than 4 million; $n=132$; total year-2000 population = 85 million) and (2) large cities, representing the upper tail of the distribution of cities (year-2000 population greater than 4 million; $n=10$; total year-2000 population = 68 million). Two groups are required because the upper tails of historic distributions behaved differently than the bulk group of cities. Once calculated separately (by extrapolating mean city populations for each Monte Carlo iteration) the two population distributions were combined, ranked, and scaled to the predicted year-2020 population (180 million).

Table 1
Six urban growth scenarios considered.

Scenario	Description[a]	Method of calculation (year-2020)	Average year-2020 PD (people km^{-2}), coefficient of variability[b]	Average year-2020 LPD (people m^{-1}), coefficient of variability[b]
Infill Only	Urban growth boundary applied to each UA	In each UA, area held constant	720 (0.40)	–
Constant Density	New development expands the urban land area but at constant density	No change in year-2000 PD distribution	610 (0.40)	–
S1	PD decline matches the smallest decadal change, 1950–2000	1970–1980 change in the P vs. A correlation	548 (0.47)	23.0 (0.94)
S2	PD decline matches the average decadal change, 1950–2000	Average change (1950–2000) in the P vs. A correlation	464 (0.41)	21.5 (0.99)
S3	PD decline matches the largest decadal change, 1950–2000	1950–1960 change in the P vs. A correlation	302 (0.47)	17.0 (0.98)
Suburban Nation	Rate of PD decline in high-sprawl cities are applied to entire dataset	Highest rate of sprawl in selected cities applied to all UAs	252 (0.40)	–

Abbreviations: PD = population density (average year-2000 PD: 610 people km^{-2}); LPD = linear population density (average year-2000 LPD: 22.0 people m^{-1}); UA = urban area; P = population; A = area.

[a] In all scenarios, population growth during 2000–2020 is 18%.

[b] Coefficient of variability among urban areas is shown in parentheses.

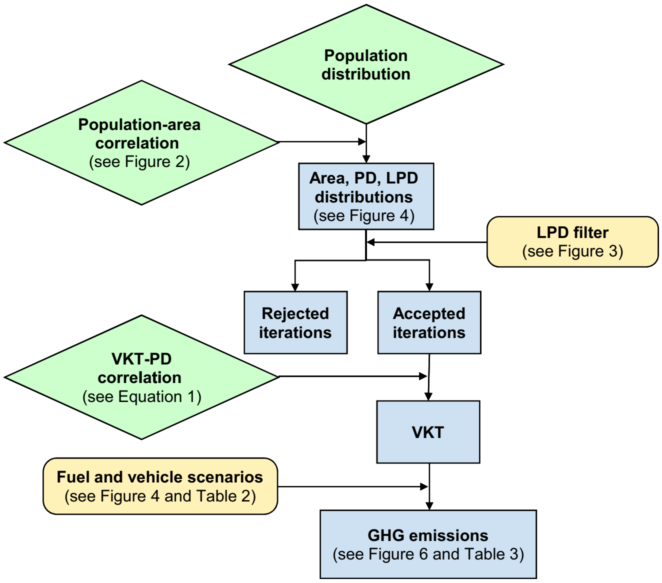

Fig. 1. Flowchart of the Monte Carlo-based method used for the urban growth simulations.

As expected, cities show a strong correlation between population and area (i.e., a larger population is generally associated with a larger area). Our low-, medium-, and high-sprawl scenarios (S1–S3) are based on the observed changes in the population–area relationship during 1950–2000. Because average population density is declining over time, a given population would require an increasing land area. For both population density and linear population density, we observed log–log correlations for most cities (population less than 4 million) and linear–linear correlations for the larger cities (population greater than 4 million). Observed and predicted correlations are shown in Fig. 2.

For each Monte Carlo urban growth scenario (S1–S3), population versus area correlations for the year 2020 were predicted based on observed historic decadal changes during 1950–2000. The predicted correlation and year-2020 population distribution were then used to calculate area, PD, and LPD distributions. These three scenarios (S1–S3) replicate historic changes and do not represent firm upper or lower limits. Scenario S1 reflects more-compact growth than S2, and S3 reflects less-compact growth than S2.

LPD is a measure of urban form that indicates the number of people along a transect of an urban area. For example, an LPD of 10 people per meter would indicate that there are 10 people in a meter-wide transect of an urban area. The US average urban LPD is 12 people per meter, or about 12 people (on average) in each meter-wide transect across an urban area. LPD values tend to be greater in denser and larger urban areas. LPD is distinct from, and behaves different mathematically than, population density. Marshall (2007) explored scaling rule aspects of LPD, e.g., LPD follows a modified version of Zipf's Law. LPD is used here because it has been shown to provide useful insight into how networks of cities expand over time. Specifically, while LPD values for a given city may vary over time, the overall distribution of values among cities varies little over multi-decadal time scales: LPD distributions for US cities are nearly constant during 1950–1990 (Marshall, 2007). The scaling rule applied here posits that LPD distributions in the coming 1–3 decades will vary little from the year-2000 distribution. Thus, the historic LPD distribution was applied as a constraint to our Monte Carlo scenarios as follows: if the year-2020 distribution of LPD values among urban areas deviated from the year-2000 distribution by more than the maximum deviation observed during 1950–2000 (35%), then that Monte Carlo iteration was removed (see Fig. 3).

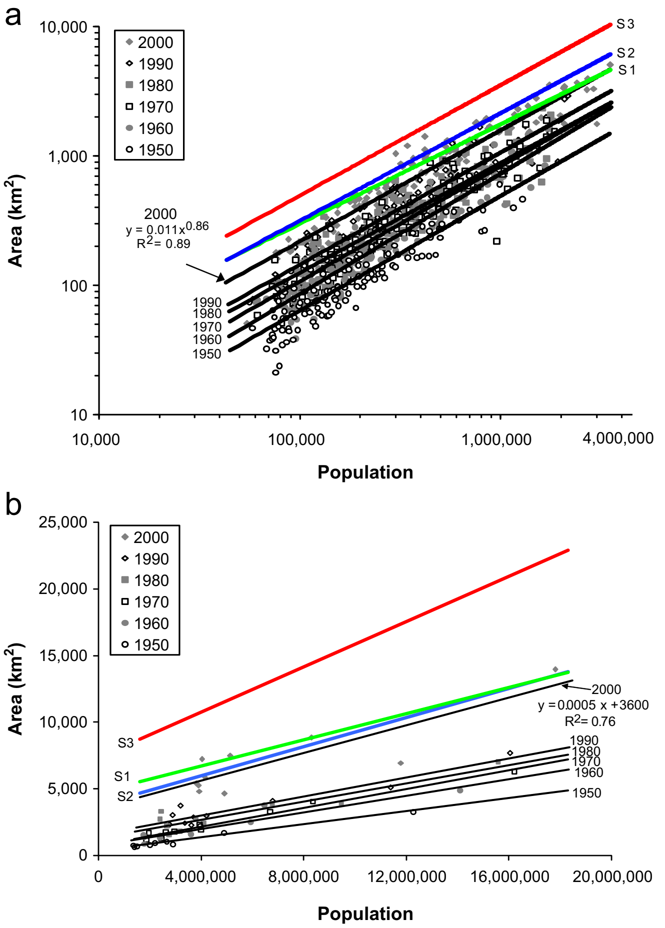

Fig. 2. Population versus area correlations for the two sets of cities: (a) most cities (year-2000 population less than 4 million people; top panel, log–log scale), and (b) large-cities (year-2000 population greater than 4 million people; bottom panel, linear scale).

To complement and extend the three Monte Carlo-based scenarios described above (S1–S3), three bounding scenarios were created: two lower bounds (Complete Infill; Constant Density) and one upper bound (Suburban Nation). These bounding scenarios calculate the population density distribution directly (i.e., without the population–area correlation) and thus are not subject to the LPD filter discussed above. For Complete Infill, the area distribution is constant. The Census-predicted 18% population growth is applied throughout the distribution, yielding a net increase in population density in all cities. Constant Density simulates that the density in each city is unchanged (i.e., all urban development in a city would be at the year-2000 average population density for that city). Suburban Nation uses two lognormal distributions to generate a year-2020 PD distribution for the two city groups (most cities; large cities). The PD decline rates from the cities that experienced the 95th percentile (largest relative) decrease in PD during 1980–2000 (for each city group) were used as inputs for this scenario. (The cities selected as this 95th percentile increase were Wheeling, WV, [PD decrease: 65%] for most cities, and Philadelphia, PA, [PD decrease: 60%] for large cities.) The result is a 2020 scenario where all US cities experience a decrease in PD similar to the observed decreases in high-sprawl cities during the last 20 years.

We used Eq. (1) to relate VKT to urban population density

$$V = 334(\text{PD})^{-0.31}, \qquad (1)$$

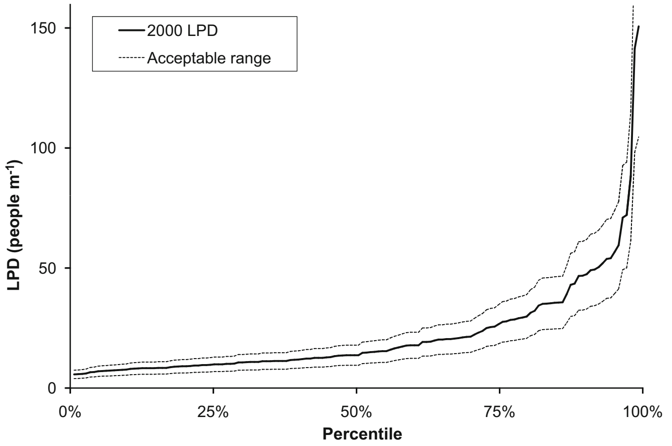

Fig. 3. The linear population density (LPD) constraint applied to urban growth scenarios.

Table 2
Fuel- and vehicle-technology scenarios considered.

	Synfuels	BAU[a]	Green fleet
Fuel emission factor ($gCO_2e\ L^{-1}$)	3840	2900	2900
Average year-2020 fuel economy (L per 100 km [mpg])	8.55 [27.5]	8.55 [27.5]	7.55 [31.1]
Year-2020 emission factor ($gCO_2e\ km^{-1}$)	329	248	219

[a] BAU = Business-as-usual technology scenario.

where PD is average population density in an urban area (people km^{-2}) and V is VKT per person per day (Marshall, 2008). Eq. (1) is based on year-2000 Department of Transportation data (US DOT, 2003) and shows a ~50% difference in daily VKT per capita between the most-dense (Miami, FL; density: 2480 people km^{-2}; VKT: 30.9 km day^{-1} person^{-1}) and least-dense (Kansas City, MO-KS; 530 people km^{-2}; 46.7 km day^{-1} person^{-1}) cities. The difference between the highest- and lowest-VKT per capita values is a factor of ~3 (Houston: 59.4 km day^{-1} person^{-1}; San Juan: 21.6 km day^{-1} person^{-1}).

2.2. Technology scenarios: vehicles and fuels

Predicting GHG emissions from mobile sources requires consideration of future transportation technology. As with urban growth, there are many possibilities for the future of fuels and vehicles. Three scenarios are proposed here to explore the interaction between VKT growth and the technologies and policies that affect fuel carbon content and vehicle efficiency (Table 2).

The base case technology scenario (business-as-usual, "BAU") assumes that gasoline remains the dominant fuel, with an unchanged life cycle assessment (LCA) emissions factor [11.0 $kgCO_2e\ gallon^{-1}$, or 2.9 $kgCO_2e\ L^{-1}$ (Farrell and Sperling, 2007)]. BAU incorporates the National Highway Traffic Safety Administration's (NHSTA) proposed corporate average fuel economy (CAFE) standards, involving phase-in of new-vehicle standards from 27.5 mpg (8.6 l per 100 km) in 2005 to 35 mpg (6.7 l per 100 km) in 2020 (NHTSA, 2003, 2008). CAFE-inclusive predicted annual on-road fuel economies calculated by Boies et al. (2008) were used in this analysis, resulting in an average on-road fleet-wide fuel economy of 27.5 mpg in 2020. CAFE standards and US on-road fuel economy are shown in Fig. 4.

The second technology scenario ("Synfuels") includes the phase-in of CAFE standards but also implements a shift from today's gasoline extraction and refining methods to a larger share of gasoline from tar sands and coal-to-liquid technology. These more energy-intensive fuels have 27–77% larger life cycle GHG emissions than today's gasoline (Farrell and Sperling, 2007). For this scenario, we assumed linear phase-in from 100% conventional gasoline in 2008 to a fuel mix of 25% coal-to-liquid, 25% conventional gasoline, and 50% tar sands in 2020. The resulting year-2020 life cycle emissions factor is 33% greater for Synfuels than for BAU. Use of more energy-intensive fuels could result in an even greater life cycle emission factor.

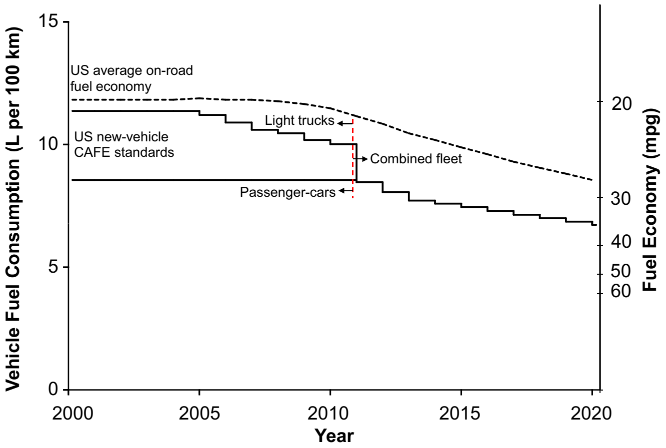

Fig. 4. CAFE standards and predicted on-road fuel economy for US passenger-vehicles (Boies et al., 2008; NHTSA, 2003, 2008). CAFE standards are separate for SUVs/light-trucks and cars before 2011 and combined for all passenger-vehicles after 2011. On-road fuel economy lags behind new-vehicle standards because of comparatively slow fleet turnover; the median vehicle lifetime is 16.9 years for cars, 15.5 years for light trucks (Davis and Diegel, 2007).

The third technology scenario ("Green Fleet") incorporates phase-in of fuel-efficient light duty vehicles (LDV), including a substantial integration of hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). Here, a linear phase-in of this alternative LDV fleet starts in 2008 and ends with a year-2020 vehicle mix of 30% PHEV, 50% HEV and 20% conventional vehicles. US average LCA GHG emission factors are 342 $gCO_2e\ km^{-1}$ for conventional vehicles, 192 $gCO_2e\ km^{-1}$ for HEVs, and 181 $gCO_2e\ km^{-1}$ for PHEVs (Samaras and Meisterling, 2008). Those values assume that the power production mix remains the same as today: 49% from coal-fired plants (EIA, 2009). Reducing the carbon intensity of electricity generation would further reduce life cycle emissions for PHEVs. The result for this technology scenario is a fleet that averages 31 mpg in 2020 rather than the predicted 27.5 mpg from CAFE alone. Here CAFE is not a binding constraint for overall fleet fuel economy because consumers choose vehicles that are more fuel efficient than CAFE standards. (Alternatively, this scenario could reflect modification of future-year CAFE standards to be more stringent than the future-year standards currently proposed.)

3. Results

During the most recent 50 years of Census data (1950–2000), US cities have shifted towards smaller overall average population density. Average PD decreased 41% during 1980–2000 which is more consistent with the decreases in PD for our higher-sprawl scenarios (S3, 50%; Suburban Nation, 59%) than for our lower-sprawl scenarios (Constant Density, 0%; S1, 10%; S2, 24%) (see Table 3). The coefficient of variation for the PD distribution is consistently 0.4–0.5 for all year-2020 urban expansion scenarios. Past and predicted PD and LPD distributions are shown in Fig. 5. Future LPD curves (averaged from the accepted

Table 3
Results for each urban growth scenario.

	Annual VKT growth, 2000–2020 (%)	Annual VKT per-capita growth, 2000–2020 (%)	Annual PD[a] growth, 2000–2020 (%)	Annual emissions ($GtCO_2e$)[b], year-2020			Total cumulative emissions ($GtCO_2e$)[b], 2000–2020		
				Synfuels	*BAU*	*Green fleet*	*Synfuels*	*BAU*	*Green fleet*
Complete Infill	0.61	−0.22	0.72	0.87	0.66	0.58	18.0	16.4	15.7
Constant Density	0.88	0.05	−0.11	0.92	0.69	0.61	18.6	16.8	16.1
S1	0.95	0.12	−0.45	0.93	0.70	0.62	18.7	17.0	16.3
S2	1.13	0.30	−1.45	0.97	0.73	0.64	19.0	17.3	16.5
S3	1.86	1.02	−3.37	1.12	0.84	0.74	20.5	18.5	17.7
Suburban Nation	2.44	1.59	−4.50	1.25	0.94	0.83	21.8	19.6	18.7

[a] Average annual growth in population-weighted average population density.
[b] Annual population growth, 2000–2020, for all scenarios: 0.83%. Year-2000 emissions: 0.80 $GtCO_2e$.

Monte Carlo distributions) are consistent with historic distributions (S1, S2) or exhibit only minor deviations (S3). Applying the LPD constraint (Fig. 3) to S1, S2 and S3 resulted in keeping 495 (50%), 453 (45%), and 52 (0.5%), respectively, of the randomly generated Monte Carlo distributions. The three bounding scenarios (Complete Infill, Constant Density and Suburban Nation) involve calculation of future PD distributions directly, without using a population–area correlation, and therefore do not employ the LPD constraint portion of the Monte Carlo-based analysis.

Future passenger-vehicle GHG emissions were calculated by combining the six urban expansion scenarios (Table 1) with the three technology scenarios (Table 2). This approach yields 18 possible outcomes, covering a range of plausible year-2020 emissions and illustrating the sensitivity of future emissions to all three variables (fuel carbon content, vehicle efficiency, and urban expansion). Results are shown in Table 3. Annual VKT growth rates in Table 3 vary from 0.6% to 2.4%. That range is (1) consistent with the 2.07% projected average annual VKT growth for 2002–2022 used by the FHWA in 2004, (2) less than the historic 2.96% average VKT growth rate during 1982–2002, and (3) consistent with the recent average VKT growth rate of 1.0% during 2002–2007 (FHWA, 2004, 2007).

In all of our scenarios, total VKT increases. In all of our scenarios except Complete Infill, VKT per capita increases. However, the amount of these increases differs among scenarios. For example, comparing S1 and S3, VKT growth rates differ by a factor of ~2 while VKT per capita growth rates differ by a factor of ~8. As highlighted in the discussion, these differences may be important for meeting GHG emission–reduction goals for the transportation sector.

Results in Table 3 indicate that urban form can have a discernable impact on GHG emissions. Under the BAU technology scenario, decreases or increases in emissions relative to year-2000 are possible, depending on which urban growth scenario is considered. For example, for Complete Infill and Suburban Nation, year-2020 emissions are 18% less and 17% more than year-2000 emissions, respectively. Similarly, with BAU fuels and vehicles, annual year-2020 (cumulative 2000–2020) emissions are 17% (8%) lower for S1 than for S3. As expected, differences among scenarios are smaller when comparing cumulative emissions than for year-2020 emissions alone.

Results in Table 3 also indicate the importance of vehicles and fuel technologies. For example, for S2, annual (cumulative) emissions are 40% (13%) higher for the Synfuels than the Green Fleet case, further illustrating the interaction among all three variables associated with passenger-vehicle emissions. Fig. 6 shows year-2020 emissions for each urban expansion scenario under each fuel and vehicle case (Synfuels, BAU, Green Fleet), relative to year-2000.

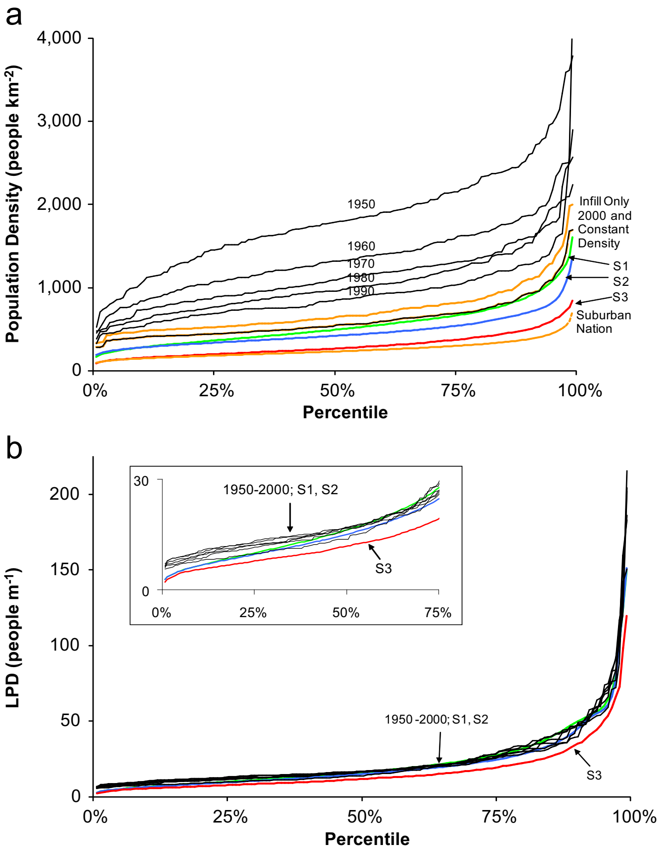

Fig. 5. Population density (PD) and linear population density (LPD): historic and predicted year-2020 distributions.

4. Discussion

Changes in average PD suggest that since 1970, rates of sprawl in US cities have been increasing. For the cities studied here, the decrease in average PD was 9% during 1970–1980, 14% during 1980–1990, and 32% during 1990–2000. If urban development continues in this manner – PD declining at an accelerating rate – then growth in total VKT could make transportation-GHG emission reduction more difficult. For scenarios considered here,

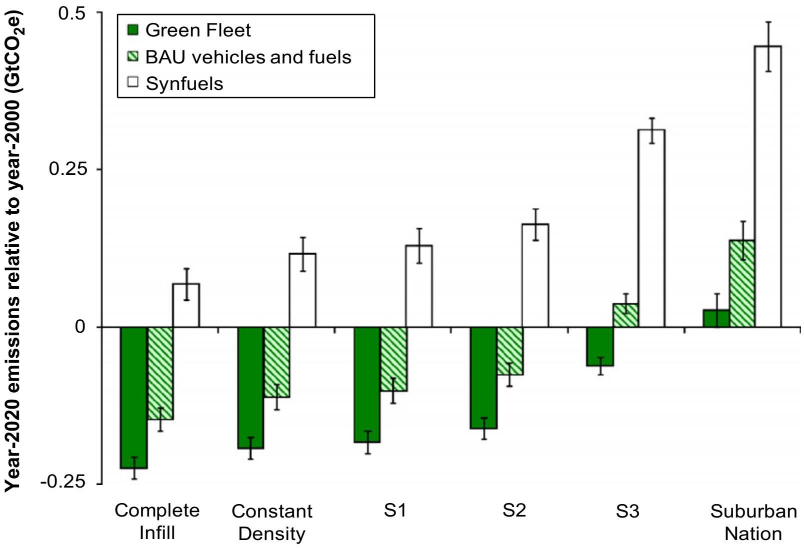

Fig. 6. Estimated year-2020 greenhouse gas emissions, relative to year-2000 emissions, for the 142 US urban areas studied. Each of the six urban growth scenarios includes the three technology scenarios. Error bars represent one standard deviation of all accepted Monte Carlo iterations.

urban sprawl reduced and in some cases eliminated the emission benefits of technology improvements.

Our results suggest that if urban form is neglected when considering GHG mitigation strategies, it is possible that increases in annual VKT could undo improvements in vehicle technology and fuels. For example, if cities experience urban growth of the type in scenario S3 (as they did from 1950–1960 and 1990–2000), the increase in total VKT (1.86% annually) could offset per-km emission reductions from currently planned improvements in CAFE standards (2000–2020 average: 1.63% CAFE reduction annually), resulting in a net increase in emissions (0.24% annual increase in GHG emissions). Conversely, even if the extreme case of Complete Infill was achieved, yet technology follows the Synfuels scenario, emissions would be 8% larger in 2020 as in 2000. Our results highlight that all three variables – vehicle efficiency, fuel carbon content and urban form – should be considered when addressing transportation GHG emissions. When enacting policies to address all three variables, interaction between terms becomes important. For example, if the fuel efficiency of the passenger-vehicle fleet doubles, then the GHG benefits of VKT reductions is reduced by a factor of 2.

Our research investigated passenger-vehicle emissions in large US cities, a source that represents ~2% of global anthropogenic GHG emissions (basis: US GHG emissions are 21% of global emissions (EIA, 2008a); transportation is 34% of US emissions (EIA, 2008b); passenger vehicles are 55% of transportation emissions (US EPA, 2002); the 142 urban areas investigated are ~50% of emissions for all US citizens (assumes emissions are roughly proportional to population)). Are the emission reductions estimated here (1.5 $\mathrm{GtCO_2e}$ for S3 versus S1, 3.2 $\mathrm{GtCO_2e}$ for the extreme cases in Table 3) significant on a global scale? To address that question we compare our results against a Climate Stabilization Wedge, defined in a highly cited *Science* paper (Pacala and Socolow, 2004) as emission reductions growing from no reductions in year-zero to 3.7 $\mathrm{GtCO_2e\,y^{-1}}$ reduction in year-50 (i.e., 92 $\mathrm{GtCO_2e}$ during 50 years, or 15 $\mathrm{GtCO_2e}$ during the first 20 years; we have converted Pacala and Socolow's numbers from GtC to $\mathrm{CtCO_2e}$). According to that article, "solving" climate change during 2005–2055 requires ~7 wedges. Approaches representing a significant fraction of a wedge merit serious consideration.

The values 1.5 and 3.2 $\mathrm{GtCO_2e}$ represent 11% and 22% of a 20-year wedge, respectively. Several factors underscore the global significance of this finding, and more broadly of using land-use strategies to reduce combustion-derived anthropogenic GHG emissions. First, the US is only ~5% of the global population and we only investigate about half of the US population. Application of land-use strategies to non-US cities may increase the total impact discussed here. Second, our analysis employs the extant relationship between density and VKT. Skillful application of land-use strategies could strengthen the GHG impact of land-use strategies (e.g., by increasing the density-VKT elasticity magnitude; see below). Third, the system we studied changes exponentially, yielding long-term emission reductions. For example, if the 20-year trends in Table 3 were extended to 50 year intervals (assumptions: CAFE standards [median vehicle lifetime: 16 years]; no change in fuels; VKT growth remains constant for each growth scenario), the emission differences of 1.5 $\mathrm{GtCO_2e}$ (S3 versus S1) and 3.2 $\mathrm{GtCO_2e}$ (Suburban Nation versus Complete Infill) increase to 9.5 and 20.4 $\mathrm{GtCO_2e}$, respectively, or 10% and 22% of a 50-year wedge. This finding highlight that shifts in urban form may be most effective as a long-term strategy. Fourth, other countries, especially developing nations, are experiencing rapid shifts in mobility while replicating developed countries' lifestyles (Gakenheimer, 1999). If the US and other developed nations are successful in designing low-carbon cities, that step would send a message that urban planning can be a tool to reduce GHG emissions. There is potential for successful (or unsuccessful) planning campaigns in the US to indirectly impact land-use patterns globally. At the same time, successful strategies may vary by city and region (Marcotullio et al., 2005). Many developing country urban areas are already much denser than US cities and thus may seek to tackle attributes other than urban sprawl as a part of any potential urban design improvements or GHG mitigation strategy—for example, addressing cases of extreme congestion or improving safety and convenience for pedestrians and bicycles.

The density–VKT relationship employed here may be strengthened (or weakened) according to the types of land-use policies in place. For example, land-use mixing and transit accessibility could increase the elasticity magnitude. The density–VKT relationship employed here (Eq. (1), above) used the mathematical form

Table 4
Sensitivity analysis, density-VKT correlation.

	Base case ($b=-0.31$)		**$b=-0.21$**		**$b=-0.41$**	
	S1	*S3*	*S1*	*S3*	*S1*	*S3*
VKT (10^{12}), year-2020	2.84	3.40	5.46	6.17	1.48	1.93
Average annual VKT growth rate, 2000–2020	0.95%	1.86%	0.92%	1.53%	0.99%	2.34%
VKT per capita, year-2020[a]	15,800	18,800	30,300	34,200	8200	10,700
Average annual VKT per capita growth rate, 2000-2020	0.12%	1.02%	0.08%	0.69%	0.16%	1.50%

[a] Year-2005 national average VKT per capita: 16,000 (FHWA, 2005).

$y=ax^b$. As a sensitivity analysis, following Stone et al. (2009), we adjusted the parameter b from the reported value, -0.31, to -0.21 and to -0.41. For S1, the result is a 92% increase ($b=-0.21$) and 48% decrease ($b=-0.41$) in year-2020 per capita travel relative to the base case ($b=-0.31$). Resulting shifts in total VKT and VKT per capita are shown in Table 4. Strengthening the density–VKT relationship (i.e., increasing the elasticity magnitude) could improve the GHG benefits of sprawl reduction. Conversely, weakening the density–VKT relationship (i.e., reducing the elasticity magnitude) by allowing low-density residents to reduce their VKT (thereby becoming more similar to high-density residents) would mitigate the GHG impacts of urban sprawl.

Our analysis builds on previous work by accounting for population and area changes to a linked network of cities while employing an urban scaling rule as a constraint. However, there are a number of limitations to our study. For example, our results are sensitive to the VKT-density elasticity, which may vary in time and space. Estimates for the value of this parameter vary (Dunphy and Fisher, 1996; Holtzclaw et al., 2002; Marshall et al., 2005). Our approach assumes that density is causally related to VKT. Travel behavior is influenced by several factors not evaluated here, including costs (e.g., fuel, time), consumer preferences, and public policy (both direct and indirect). Increases in energy prices and demand-side management strategies (e.g., mileage taxes, congestion charge zones) would impact vehicle travel and also are not addressed here. This study models GHG emissions from passenger vehicles only, thereby omitting emissions from mode shifts (e.g., mass transit) (Schipper et al., 2000), non-road (e.g., air) travel, and non-mobile sources (e.g., buildings) (Codoban and Kennedy, 2008; Vandeweghe and Kennedy, 2007). Additional, more comprehensive, analysis of the GHG impacts of urban form is warranted. Despite these important limitations, we believe that the results and the novel approach presented here provide a useful addition to this literature. Given the inherent uncertainties in forecasting long-term urban growth for a single urban area, Monte Carlo investigation of a linked set of urban areas, with conservation in total population growth, may yield additional insight (and potentially more reliable results) as compared to aggregation of several single-city studies. Further investigation of urban scaling and network science (Batty, 2008) would help delineate strengths and weaknesses of various approaches.

Energy, environment, transportation systems, and land-use patterns are inherently linked. Moreover, different types of urban growth have different benefits and costs. Examples of policies in the US that are commonly cited as encouraging compact growth include zoning for mixed use and for transit corridors, removing building height restrictions (or adding flexibility), raising density maximums, and reducing or eliminating minimum parking regulations (Downs, 2005). Many of those steps involve less regulation, not more. Improved public health, livability, efficient public services, and access to affordable transportation are non-pecuniary benefits that may result from compact development (Carruthers and Ulfarsson, 2008; Downs, 2005; Frank et al., 2004). For example, studies indicate that the built environment and travel patterns (e.g. land-use mix, walk distance per day, time spent in a vehicle) are related to rates of obesity (Brown et al., 2008; Frank et al., 2004; Marshall et al., 2009), suggesting that certain types of city design can have a positive impact on public health. On the other hand, if cities are denser but VKT and emissions of toxic air pollutants are not reduced significantly (for example, because the density-VKT elasticity magnitude is small, or because of weak vehicle emission standards), then compact cities could experience worsening air pollution (Marshall et al., 2005). Increased congestion (both in low- and high-density cities) could reduce average vehicle speeds, potentially worsening emissions and exposures. Thus, from the standpoint of urban air pollution, improvements in fuels and vehicles may be an important precursor to compact development. More research is needed to explore how shifts in urban land use could yield co-benefits rather than trade-offs among environmental goals.

Shifts in urban form may represent valuable GHG reduction tools in part because they do not require new technologies. Proper reform of policy on urban growth may take considerable political willpower but the long-term benefits resultant from these policies may be crucial to the success of GHG mitigation from the transportation sector.

5. Conclusion

The way we choose to build our cities will impact transportation greenhouse gas emissions. We employed an urban scaling rule to predict realistic future high- and low-sprawl scenarios for 142 US urban areas representing 56% of the total US population. Moderate reductions in carbon emissions can be achieved by promoting specific types of urban development—for example, compact growth. We found that emissions savings resultant from these scenarios would account for 10–22% of a Climate Stabilization Wedge.

Declining average population density during 1980–2000 for these 142 cities more closely resembles the high-sprawl scenarios (S3, Suburban Nation) than those of low-sprawl (S1, S2, Constant Density). If this trend continues, valuable innovations in fuel carbon content and vehicle technology could be offset by increases in vehicle travel. Comprehensive, effective, long-term climate-change mitigation for US urban vehicle emissions will likely need to incorporate components from all three strategies: (1) improving vehicle efficiency, (2) lowering the carbon content of fuels and (3) reducing VKT growth rates.

Acknowledgments

S Hankey was funded in part by the Center for Transportation Studies (CTS) at the University of Minnesota and by the Minnesota state legislature. This article has not been reviewed or endorsed by the funders; opinions expressed herein reflect the views of the authors only and not necessarily of the funder.

Appendix 1. Supporting Information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2009.07.005.

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