Reducing Motor Vehicle Greenhouse Gas Emissions in a Non-California State: A Case Study of Minnesota

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Approaches for reducing greenhouse gas (GHG) emissions from motor vehicles include more-efficient vehicles, lower-carbon fuels, and reducing vehicle-kilometers traveled (VKT). Many U.S. states are considering steps to reduce emissions through actions in one or more of these areas. We model several technology and policy options for reducing GHGs from motor vehicles in Minnesota. Considerable analysis of transportation GHGs has been done for California, which has a large population and vehicle fleet and can enact unique emissions regulations; Minnesota represents a more typical state with respect to many demographic and transportation parameters. We conclude that Minnesota has a viable approach to meeting its stated GHG reduction targets (15% by 2015 and 30% by 2025, relative to year 2005) only if advancements are made in all three areas—vehicle efficiency, carbon content of fuels, and VKT. If policies focus on only one or two areas, potential improvements may be negated by backsliding in another area (e.g., increasing VKT offsetting improvements in vehicle efficiency).

Introduction

Transportation is the largest end-use source of greenhouse gas (GHG) emissions in the United States. Total CO_2 emissions from transportation in the U.S. increased 1.5% annually (on average) from 1990 to 2007 (*1*). Average U.S. (global) transportation emissions per capita were 6.7 (1.0) tCO_2 $person^{-1}$ y^{-1} in 2004 and increased 0.38% (1.0%) annually during 1990−2004 (*2*−*5*). In the U.S. transportation sector, most energy consumption is from petroleum-based fuels (95%), most direct GHG emissions are CO_2 (93%), and most CO_2 emissions are on-road (82%) (*2, 3*).

For many important air pollutants such as carbon monoxide and reactive hydrocarbons, emission reductions have historically been achieved via on-board technologies such as catalytic converters. Such technologies do not currently exist for CO_2. Instead, emission reductions strategies generally aim to influence (1) vehicle energy efficiency, (2) fuel carbon content, or (3) transportation demand.

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State and national efforts to reduce transportation-GHG emissions have typically been contentious and of limited effectiveness. In the absence of a comprehensive and aggressive national GHG reduction policy, many U.S. states established GHG reduction targets and are pursuing those goals. Here, we evaluate quantitatively how a state can reduce transportation-GHG emissions through strategies linking three main options: improving vehicle efficiency, lowering fuel carbon content, and reducing demand (vehicle kilometers traveled; VKT).

States play an important and unique role in environmental policy. States have different legal constraints and opportunities than the federal government, and with their diversity of political views often serve as policy laboratories. Approximately 18 U.S. states would rank in the top 50 GHG emitting nations if U.S. states were considered as independent countries (*6*). As of mid-2009, approximately 33 states have a climate change action plan, approximately 15 states have adopted California's vehicle GHG emissions standards, and one state (California) has enacted a low-carbon fuel standard (*7, 8*). California, often viewed as a leader in transportation emissions reduction efforts, has distinct demographic, geographic, and economic attributes (e.g., environmentally minded populace; large coastline potentially threatened by sea-level rise; large agricultural economy and a constrained water supply, both potentially threatened by changes in climate; large vehicle market). In addition, unique among the states, California has legal authority to enact more stringent light-duty vehicle (LDV) emission standards than the federal rules (*9*).

California is well studied, but it is an outlier. Locations that are more representative remain under-investigated in the potential for state environmental policies to reduce transportation-GHG emissions. We studied Minnesota in response to recently enacted state legislation and because, relative to California, Minnesota may be more representative of a typical state for several attributes relevant to transportation emissions (e.g., population: MN 5.2M, median state 4.3M, CA 37M (*10*); registered LDVs: MN 2.6M, median state 1.9M, CA 20M (*11*); travel [vehicle-km $person^{-1}$ y^{-1}]: MN 17.7K, median state 17.1K, CA 14.5K (*12*); motor gasoline consumption [L $person^{-1}$ y^{-1}]: MN 2.0K, median state 1.9K, CA 1.7K (*13*); proportion of electricity from coal, which impacts emissions from plug-in vehicles: MN 59%, U.S. 49%, CA 1% *13, 14*). (These data indicate that Minnesota is representative, yet "above average" (*15*).) Minnesota's GHG reduction targets (see below) are similar to targets adopted by other states.

Methods

In 2007, Minnesota enacted GHG emission reduction targets: 15% by year 2015, 30% by year 2025, and 80% by year 2050, referenced to year 2005 levels (~155 million metric tons CO_2-equivalents [$MMtCO_2e$]) (*16*). Our investigation evaluates the first two targets (15%, 30%) quantitatively and the last target (80%) qualitatively. Emission scenarios are developed by considering each of the three terms in eq 1 separately (*17*):

$$\text{Emissions} = \underbrace{\left(\frac{\text{Liters}}{\text{Kilometer}}\right)}_{\text{Fuel Consumption}} \times \underbrace{\left(\frac{\text{Mass of Carbon}}{\text{Liter}}\right)}_{\text{Fuel Carbon Content}} \times \underbrace{\left(\text{Vehicle Kilometers Traveled}\right)}_{\text{Activity}}$$

or

$$E = F \times C \times A \quad (1)$$

We previously evaluated several technology and policy scenarios (*18*) using the Long-Range Energy Alternatives

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Planning (LEAP) tool (*19*) and the Center for Clean Air Policies (CCAP) calculator (*20*). We focused mainly on light-duty vehicles (LDVs), which in Minnesota produce ∼63% of transportation GHG emissions (∼60% U.S., ∼48% globally) (*21*−*23*). This article updates our previous work by incorporating more recent data, including vehicle standards proposed by the Obama administration. Emissions from heavy-duty vehicles and from nonroad vehicles such as trains, ships, and airplanes are discussed separately below.

Historical fuel consumption and VKT data for LDVs were obtained from the Minnesota Pollution Control Agency, the Minnesota Department of Transportation, and the Energy Information Agency. Year 2007 estimates for Minnesota are 10.3 billion L of on-road motor gasoline (1980 L $person^{-1}$) and 86.0 billion vehicle-km (16,600 vehicle-km $person^{-1}$), indicating average fuel consumption of ∼11.9 L 100-km^{-1} (∼19.8 miles gal^{-1} [mpg]) (*21, 24, 25*).

Vehicle Efficiency. We modeled the Corporate Average Fuel Economy (CAFE) standards proposed in May 2009, targeting a fleet average of 6.6 L 100-km^{-1} (35.5 mpg) in year-2016. These rules will be harmonized fuel consumption/GHG standards, developed jointly by the U.S. DOT and EPA (*26*). CAFE standards represent a do-nothing option for Minnesota. Alternatively, the state can adopt California's LDV GHG standards. California has agreed that compliance with the federal harmonized standards will be considered compliance with their standard through 2016, but retains the option to impose rules more stringent than CAFE thereafter (*27, 28*) (see Supporting Information [SI]). Annual VKT by vehicle age, fleet age profiles, and new vehicle sales projections were based on data from the Transportation Energy Data Book (*29*), Energy Information Administration forecasts for the West North Central region (includes Minnesota) (*30*), and previous LEAP models. The modeled median vehicle lifetime is 8 y (cars) and 6 y (light-duty trucks) and the 90th percentile lifetime is 15 y (cars) and 16 y (light-duty trucks).

Low Carbon Fuels. We analyzed three Minnesota policy scenarios targeting compliance with a low-carbon fuel standard (LCFS). An LCFS is typically a market-based mechanism that requires fuel providers to reduce fuel carbon content by a specified percentage over a given period of time but allows flexibility in selecting which fuels to blend and allows trading of carbon credits to meet goals. Minnesota is the fourth-largest producer of ethanol among U.S. states and mandates 10% ethanol by volume in gasoline; this mandate is planned to increase to 20% in 2013 (*31, 32*). We assumed that Minnesota's low carbon fuel strategies for years 2015 and 2025 will emphasize ethanol. Other biofuels may play a larger role later. The scenarios we modeled are (1) doubling the ethanol content of gasoline sold in Minnesota from 10% (current state law) to 20% by volume assuming production continues with "business-as-usual" corn feedstock and a natural gas-powered process; (2) doubling the ethanol content from 10% to 20% with corn feedstock but using a dry-mill process in distilleries burning stover (leaves and stalks) to generate process heat; (3) maintaining the ethanol content at 10% but replacing corn feedstock with cellulosic material and converting to a process using cellulose-derived energy (see SI).

GHG emissions during fuel production, refining, and distribution may be comparable to or greater than emissions during fuel combustion. Our comparisons among fuels therefore account for both in-use emissions and upstream (lifecycle) emissions. Values employed were obtained from Farrell et al. (*33*). GHG emissions associated with converting land to biofuel crops were not explicitly modeled, but are discussed below.

Vehicle Kilometers Traveled Reduction. Our modeling of VKT and VKT-reduction policies incorporated two approaches. First, we used three estimates from the Minnesota Department of Transportation (DOT) of annual growth in statewide VKT: no growth (0%), nominal growth (0.9% annually, or roughly the projected population growth; i.e., this scenario involves almost no change in per capita VKT), and high growth (2.3% annually, or ∼1.4% annual growth in per capita VKT). For comparison, average annual per capita VKT growth in Minnesota (the U.S.) was ∼2.8% (∼2.3%) during years 1991−2002 and ∼0.7% (∼1.1%) during years 2002−2006 (*34*). However, Minnesota's VKT was unchanged during years 2005−2007, and declined slightly in year 2008 (*24, 35*). While VKT is unlikely to continuously decrease from 2008 until 2015 or 2030, the recent shift in trends suggests that VKT may be somewhat more elastic than the scenarios modeled here. The goal of these three scenarios is to provide a sensitivity analysis; they capture a range of possible impacts from diverse issues such as fuel price volatility, economic cycles, and traffic congestion, and indicate the extent to which VKT variations affect GHG emissions.

Second, we evaluated three types of policies aimed at influencing VKT: coordinated transportation and land-use planning ("smart growth"), shifts in mass-transit infrastructure, and pricing strategies. Comprehensive investigation of each approach was beyond the scope of our research; instead, we applied available estimates for other regions using the CCAP calculator (*20*). Smart growth is a regional approach that incorporates several complementary measures such as transit-oriented and infill development, and in general strives to capture the benefits associated with linking transportation and land use planning. We considered a sequence of three smart growth cases—limited, comprehensive, and aggressive—that incorporate a progressively increasing emphasis on infill development paralleled by a decreasing use of greenfields. Light-rail transit, bus rapid transit, commuter rail, and general transit improvements were evaluated as transit infrastructure shifts, which aim to provide or upgrade alternative travel modes that potentially offer improved efficiency. Pricing strategies modeled were pay-as-you-drive (PAYD) insurance and parking plans. PAYD insurance converts an upfront vehicle usage fee (automobile insurance is generally paid per time, e.g., per year) into a marginal usage fee (e.g., per kilometer), with evidence suggesting that replacing upfront costs with marginal costs may reduce VKT (*36*). Employer and municipal parking plans pass on to consumers the cost of parking, which is often hidden, embedded in the cost of other goods and services. The VKT policies are summarized in Table 1. In a separate analysis (see Figure 3), we use national data to compare GHG emissions among modes (e.g., cars versus buses).

Because the strategies considered are generally most effective when implemented in urban areas, for all strategies but PAYD insurance we assumed that strategies and impacts would occur only in the Minneapolis-St Paul region (MSP). MSP represents approximately 60% and 47% of the state's population and VKT, respectively. Our approach is based on available quantitative evidence, but by applying results from non-Minnesota cities, our investigation implicitly assumes that MSP is like other urban areas, that the transportation models employed elsewhere to generate our results are accurate, and that the impact of smart growth changes will be similar in the future as they were in the past. As discussed below, our VKT reduction estimates are likely conservative.

Results

2015 and 2025 Goals. Our scenarios estimate Minnesota emissions over time based on policies affecting each of the parameters in eq 1. The projections incorporate LDV emissions only; further reductions are possible from areas such as

TABLE 1. Estimated Minnesota Statewide VKT Impacts of Selected Strategies

strategy	key scenario assumptions	percent increase in statewide VKT, 2005–2025	percent statewide year-2025 VKT reduction, relative to a do-nothing scenario
do-nothing (0.9% annual VKT increase)		19.6	0.0
smart growth	year 2030 VKT in MSP reduced relative to do-nothing by:		
1. limited	5%	17.8	1.5
2. aggressive	10%	15.5	3.4
3. comprensive	15%	13.3	5.3
mass-transit			
4. general improvements to existing transit		19.3	0.3
5. construction of commuter rail	single rail line planned for Minneapolis rail network in Minneapolis/St Paul	19.5	0.1
6. construction of light rail transit network	region more extensive than currently planned	17.0	2.2
7. construction of bus rapid transit network	extensive network in Minneapolis/St Paul region	17.0	2.2
pricing strategies			
8. pay-as-you-drive insurance	10% penetration statewide	18.4	1.0
9. employer/municipal parking-pricing plans	5% of Minneapolis/St Paul population affected	19.3	0.3

efficiency improvements in heavy-duty on-road vehicles and aircraft (see below). Our estimates incorporate lifecycle GHG emissions.

Figure 1a shows the impact of the CAFE and California vehicle standards individually. For both standards, emissions are reduced over time, but neither standard alone meets the goals. Because of the relatively modest influx of new vehicles (~5% annually (*30*)), fleet fuel economy lags new-car standards, delaying the effect of new-vehicle policies. The U.S. may have weaker fuel economy standards than other countries have; larger improvements in fuel economy may be viable (see SI).

Figure 2 shows average fuel carbon intensity (AFCI; units: $gCO_2e\ MJ^{-1}$) projected to 2030 for a base case and the three LCFS scenarios described above. Modest emission reductions are possible based on fuel standards. However, it is the *quality* of the fuel, i.e., lifecycle AFCI as determined by feedstock and production process, more so than the *quantity* produced, that determines GHG reductions from ethanol. This is important in states such as Minnesota that anticipate an increased ethanol mandate (*31*). Currently, only one of Minnesota's 18 ethanol producers uses biomass for process heat, but an LCFS policy of the type we modeled would provide an incentive for others to do so. The emissions impact from land use changes (LUCs) is uncertain and was not included in our analyses. Recent work suggests that corn ethanol LUC emissions are ~20–30 $gCO_2e\ MJ^{-1}$ (*37*). Assuming the values in Figure 2, LUC emissions of this magnitude would eliminate the estimated GHG reductions from increased use of Midwest average corn-based ethanol as it is produced today, and meeting the LCFS would require earlier use of fuels with lower non-LUC emissions, e.g., the cellulosic ethanol modeled in Scenario 3. Appropriate quantification of LUC emissions is necessary for establishing a scientifically valid LCFS.

Table 1 summarizes the reductions projected for total state VKT from the policies we modeled, and key assumptions for the estimates. The estimated VKT reductions from each strategy are not directly additive; synergies and co-benefits may exist. Figure 1b indicates that VKT growth can strongly impact, and in some cases offset, the emissions reductions from other policy actions. Using the three VKT growth scenarios from the Minnesota DOT and assuming that CAFE and LCFS policies are in place, the 2015 and 2025 targets can be met with these two policies if there is no VKT growth. The goals are approached but not achieved for nominal VKT growth (0.9% annually). With high VKT growth (2.3% annually), reductions fall well short of the goals despite strong improvements in vehicles and fuels emissions. These findings emphasize that VKT growth can overwhelm technology improvements in vehicles and fuels (*38*).

Figure 1a also shows several policy combinations. The year 2015 goal is almost met and the year 2025 goal is exceeded by the two-policy combination of CAFE standards and the LCFS. Relying on this combination alone, however, risks that VKT increases will offset some of the efficiency and fuel emissions reductions (see below). [Two of the scenarios in Figure 1a assume comprehensive smart growth (Table 1; 0.6% annual growth in statewide VKT); the remaining three scenarios assume nominal (0.9%) annual growth in statewide VKT.] The 2015 goal is met and the 2025 goal is exceeded with the three-policy combination of the California vehicle standards, the LCFS, and comprehensive transportation and land use planning strategies.

While specific-year GHG reduction targets are appropriate for policy implementation, cumulative emissions ultimately determine overall GHG atmospheric concentrations and the resulting impact on climate. Table 2 summarizes the LDV emissions levels and percent reductions for the transportation sector achieved for years 2015 and 2025 under the policies, and shows cumulative emission reductions for 2005–2030.

2050 Goal. Uncertainty around all model variables is large when projected ~40 years. Federal and state agencies do not forecast parameters needed for modeling emissions to 2050.

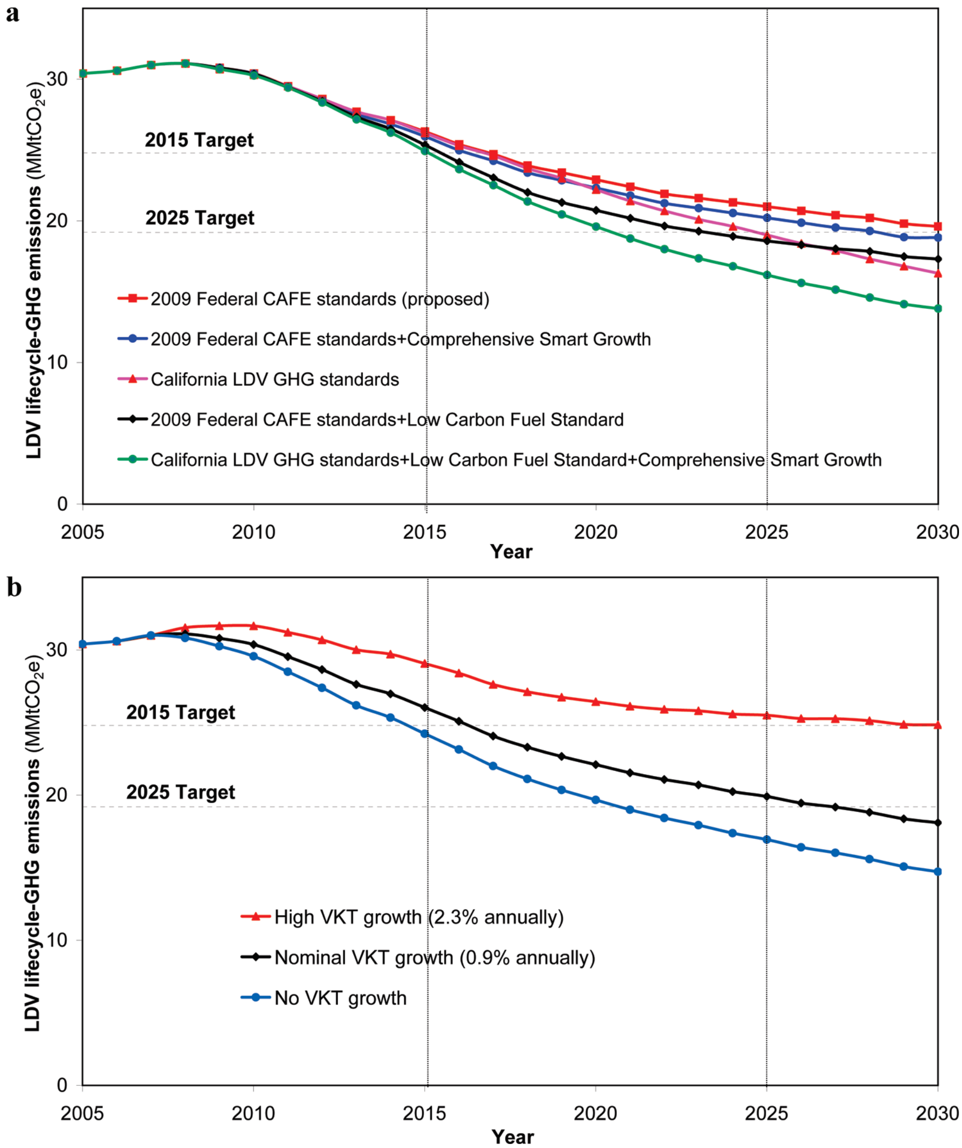

FIGURE 1. Projected Minnesota light-duty vehicle (LDV) lifecycle-GHG emissions from policy and VKT growth scenarios, compared to 2015 and 2025 reduction targets. (a) Individual and policy combinations. (b) Federal CAFE standards (proposed May 2009) plus Low Carbon Fuel Standard with three Minnesota VKT growth projections.

We qualitatively reviewed some of the considerations for moving toward Minnesota's 2050 reduction goal (80% relative to 2005).

Minnesota electricity generation has a higher reliance on coal (see Introduction) and a correspondingly higher GHG emission factor compared to the national grid (average GHG emissions from electricity [units: $kgCO_2\ MWh^{-1}$] are 692 in Minnesota and 605 nationally (*14, 39*)). Our modeling suggests that in Minnesota, life-cycle emissions per vehicle-kilometer for plug-in hybrid electric vehicles (PHEVs) will not be less than those from standard hybrid-electric vehicles until 2020, when the state's electrical generation has further decarbonized in compliance with Minnesota law (*18*). If the state-mandated schedule for reducing electricity GHG emissions were delayed, the GHG benefit from PHEVs would also be delayed. We therefore view plug-in vehicles as more appropriate for meeting Minnesota's 2050 goals. Conventional (non-plug-in) hybrid-electric vehicles may play a role in meeting both short- and long-term goals in Minnesota. Continued research on alternative liquid fuels such as ethanol from prairie grass and dimethyl ether as a replacement for diesel should also be part of a long-term renewable energy strategy portfolio.

Transportation and land-use policies can have a discernible impact on travel behavior. Furthermore, vehicle mode shifts could represent a key strategy for the long-term mitigation of VKT growth and subsequent GHG emissions. To explore this issue, assuming current fuel mixes and utilization levels, we compare (Figure 3a) average emissions per person-km by mode for current conditions (national averages) and at maximum capacities (minimum possible emissions per capita). Figure 3a is based on the current transportation system, e.g., no change in vehicle technology, fuels, or utilization. We observe that mode shifting can reduce emissions, though in some cases the emission differences by mode are modest. At average capacity, for within-city travel, emissions are 44−56% lower for rail than for cars or SUVs. At maximum capacity, (i.e., lowest per-person emissions) for between-city travel, values are 67−74% lower for bus or rail compared to aviation. Increasing the utilization (percent of seats that are occupied) would reduce emissions per person-kilometer for all modes; the available room for improvement varies among modes. Emission reductions can also be achieved by shifting freight modes (Figure 3b). For example, trains are ∼13× more fuel-efficient than trucks (163 versus 13; units: tonne-km L^{-1}). For passengers and freight,

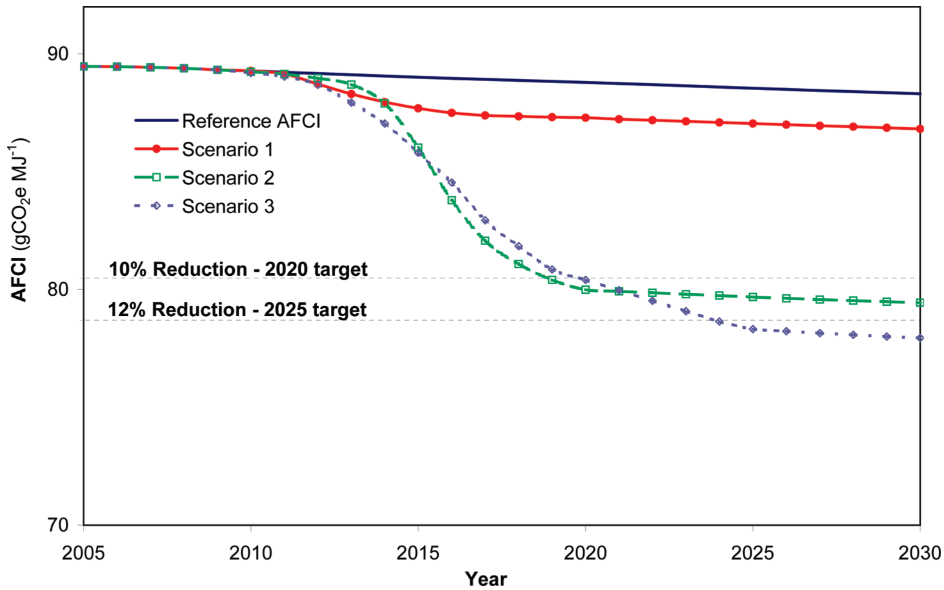

FIGURE 2. Projected average fuel carbon intensity (AFCI) for the light-duty vehicle fleet under different feedstock and process scenarios, with a Low Carbon Fuel Standard AFCI target reductions of 10% in 2020 and 12% in 2025 (*18*). The reference scenario maintains the current ethanol mix with gasoline at 10% by volume and assumes corn feedstock and natural gas process fuel. Scenarios 1 and 2 double ethanol volume in gasoline to 20% assuming corn feedstock; process heat for ethanol refining comes from natural gas for Scenario 1 but from stover for Scenario 2. Scenario 3 maintains the current ethanol 10% by volume but assumes cellulosic feedstock.

TABLE 2. Target Year and Cumulative LDV Emissions for Minnesota Transportation GHG Reduction Policies and Policy Combinations

scenario[a]	[$MMtCO_2e$ (% reduction)] year 2015 emissions[b]	year 2025 emissions[b]	cumulative 2005−2030 emissions[c]
Federal CAFE Standards[d]	26.3 (−11%)	21.0 (−25%)	653 (−20%)
Comprehensive Smart Growth plus Federal CAFE Standards	26.0 (−12%)	20.2 (−27%)	641 (−22%)
California LDV GHG Standards[e]	26.2 (−11%)	19.0 (−31%)	630 (−23%)
Low Carbon Fuel Standard plus Federal CAFE Standards	25.4 (−14%)	18.6 (−32%)	618 (−25%)
California LDV GHG Standards plus Low Carbon Fuel Standard plus Comprehensive Smart Growth	24.9 (−15%)	16.2 (−38%)	588 (−28%)

[a] Annual VKT growth rates with and without Comprehensive Smart Growth are 0.6% and 0.9%, respectively. [b] Percentages given for years 2015 and 2025 are reductions from year 2005 transportation sector emissions (37.2 $MMtCO_2e$; tailpipe emissions only (*16*)), at stated LDV lifecycle emissions. Year 2015 and 2025 goals for transportation sector are 15% (5.6 $MMtCO_2e$) and 30% (11.2 $MMtCO_2e$) reduction, respectively, relative to year 2005. [c] Percent values for cumulative emissions are reductions relative to baseline LDV cumulative emissions value of 820 $MMtCO_2e$ for years 2005−2030. For baseline growth, LDV emissions (units: $MMtCO_2e$) are 30.4, 31.0, and 32.4, in years 2005, 2015, and 2025, respectively. [d] CAFE scenarios assume 2009-proposed CAFE/GHG harmonized standards through 2016, 2% annual efficiency increase 2017−2020, 1% annual efficiency increase 2021−2030. [e] California standards scenarios assume same efficiencies as CAFE through 2016, GHG reduction equivalent of 5% annual efficiency increase 2017−2020, GHG reduction equivalent of 3% annual efficiency increase 2021−2030.

increasing the utilization of more energy efficient modes such as rail may require a sustained investment in transit infrastructure.

Discussion

Need for Policy Action in Three Areas. Our analysis examined a limited set of transportation GHG-reducing policy actions and combinations thereof that Minnesota could implement. We conclude that no single policy for vehicle efficiency, fuel carbon content, or VKT will achieve the state's targets. Instead, only a combination of policies addressing reductions from each of these parameters achieves the goals for 2015 and 2025. The multiplicative construct of eq 1 implies that all three parameters must be addressed simultaneously to prevent growth in one or two of the factors negating reductions in the other one or two factors (e.g., a 10% reduction in two factors would be offset if the third factor increased 24%). We believe that this observation is sometimes missing from federal and non-California state GHG policy discussions, which often consider fuels and/or vehicle efficiency but not VKT.

Reductions from Non-LDVs. Our modeling focused on LDVs, but opportunities exist for reducing GHG emissions from heavy-duty and nonroad vehicles. Heavy-duty on-road vehicles could contribute nominally 13% of the transportation sector's reduction goals in 2015 and 2025, assuming more widespread use of efficiency-improving technologies and operational changes available now (see SI). In some cases, states lack legal authority for action, e.g., states may not require international airplane companies to use more efficient engines. We have not explored opportunities for novel pricing strategies, e.g., tiered corporate fees at airports that provide

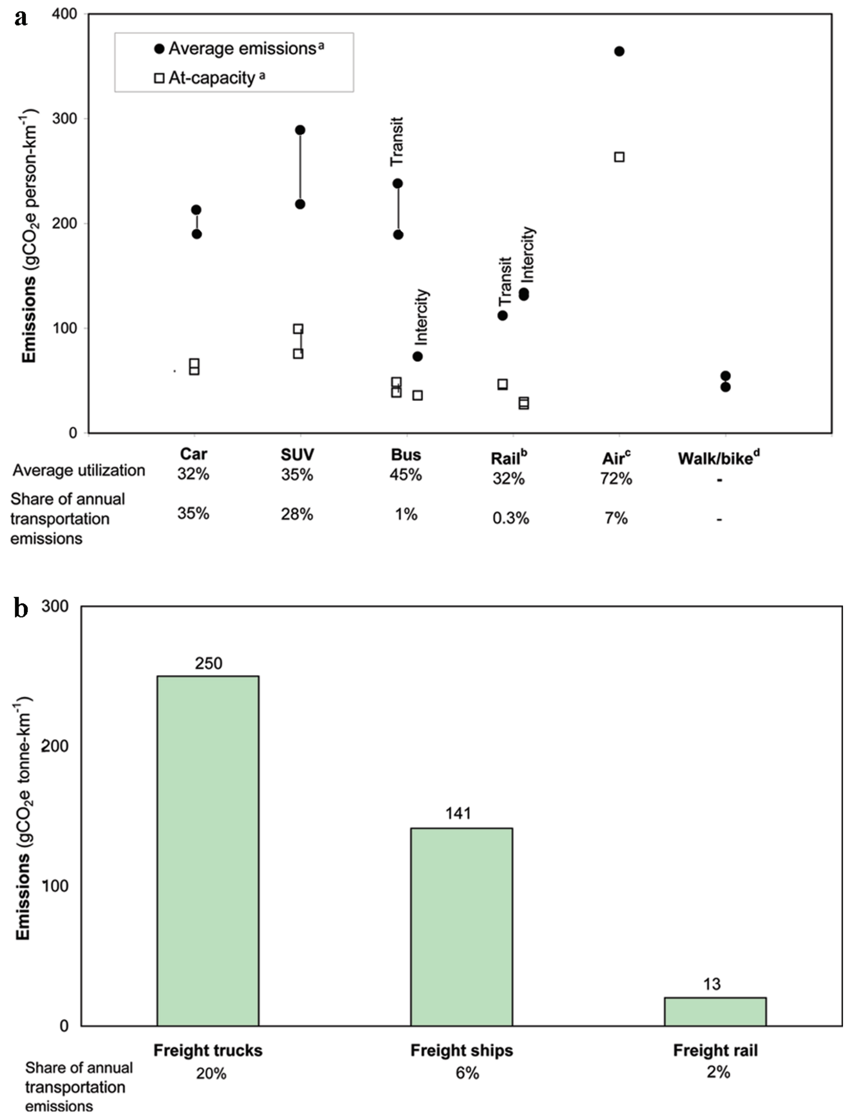

FIGURE 3. GHG emissions by mode, per person-km or tonne-km[e]. Values are for the U.S. (a) Passenger modes. (b) Freight modes (*2, 49*).

[a] Emission factors ($gCO_2e\ L^{-1}$): diesel (3300) (*29*), gasoline (2880) (*33*), jet fuel (3100) (*50*) (scaled to LCA with diesel as basis); and electricity (670 $gCO_2e\ kWh^{-1}$) (*51*). Mode capacity (seating): car (5), light-duty truck and sport-utility vehicle (SUV) (5), bus (43), rail (transit: 60; intercity: 120), and air (133) (*2, 52*). Mode load factors (persons per vehicle): car (1.6), SUV (1.7), transit bus (8.8), intercity bus (21.2), transit rail (22.5), intercity rail (29.6), air (96.2) (*2, 49*). Average fuel economy for passenger-vehicles (mpg): car (22.4), SUV (18.0) (*53*). Estimates present a range of results for each mode according to data availability from multiple sources (*2, 49*). Utilization is ridership divided by capacity. Because of differences among transportation modes in the nature of services, routes available, and other factors, it is difficult to calculate comparable national energy intensities among modes. Values shown here are averages and may vary by region or across time. [b] Transit rail includes within-urban light and heavy rail. Intercity rail includes commuter and between-urban (i.e., Amtrak) rail. Fuel mixes for all vehicular modes were taken from (*2, 49*). Passenger rail fuel mixes are heavy rail, 100% electric; commuter rail, 41% diesel, 59% electric; intercity rail, 61% diesel, and 39% electric. [c] Aviation emissions presented here include a Radiative Forcing Index (RFI) of 2.6, which accounts for high-altitude emission effects (e.g., contrails). Source: ref *54*, sections 6.2.3. and 6.6.5. Only domestic flights are shown here. All energy use is attributed to passengers (cargo use on passenger-flights is not taken into account). [d] Walking and biking use Metabolic Equivalent of Task (MET) factors from (*55*). Assumptions: US average diet: 3800 Calories $person^{-1}\ d^{-1}$ (*56*); average persons per household: 2.64 (*57*); average GHG emissions per household attributed to food: 8.1 tCO_2e (*58*); calories burned are "new" (i.e., more daily consumption is necessary). The estimates show the range of emissions for men and women when biking or walking. [e] In general, international and domestic values may differ. For example, for waterborne freight, GHG emissions per tonne-km may be significantly lower for international (*59*) than for domestic (*2, 49*) because of vessel size differences.

incentives for efficient engines or low-carbon fuels. For commercial sectors such as trucking and airplanes, companies inherently seek relatively fuel-efficient operations because fuel is a large fraction of operating costs. Opportunities for reducing emissions and operating costs, such as the EPA SmartWay program for trucking fleets, have been shown to be effective (*40*). As noted above, mode shifting may offer a major opportunity for GHG reduction from freight transport.

Conservative Estimates of VKT Reduction Policy Impacts. Table 3 presents impacts of smart growth that have been estimated for some other urban areas (*20*). Our results for the MSP region (Table 1) are at or below the range of values estimated for other areas. In addition, we likely underestimate the maximum potential VKT impact of transportation and land-use planning because we modeled only one urban area in the state and because the model did not account for a greater impact from VKT-reducing policies

TABLE 3. Comparison of VKT Reductions from Urban "Smart Growth"-Type Policies, Relative to a Business-as-Usual Scenario[a]

area	years	percent urban VKT reduction, relative to a do-nothing alternative, in final year
Albany, NY	2000−2015	7−14
Portland, OR	1995−2010	6−8
Puget Sound, WA	2005−2050	10−25
Sacramento, CA	2001−2015	7
Salt Lake City, UT	2000−2020	3
California[b]	2000−2020	3−10
Minnesota (this study)	2004−2025	0−5
U.S. Metropolitan Statistical Areas[c]	2000−2030	1−8

[a] Non-Minnesota values are adapted from ref *20*, except last row is from ref *41*. [b] California values are combined reductions for 15 Municipal Planning Organization regions (*48*). [c] Based on U.S. Census designations for metropolitan areas as defined in 1999 (*41*).

if gasoline prices rise. Our results (0−5% reduction by 2025) are consistent with a recent report by the National Academy of Sciences suggesting that smart growth may yield a 1−8% reduction in VKT by 2030 relative to a baseline (*41*). A large body of research documents that urban form can impact VKT, but there are still significant uncertainties; more work is needed regarding the potential for GHG mitigation from energy-efficient urban form (*42*).

Economic Impacts of GHG Reduction Policies. A comprehensive economic assessment for Minnesota of the transportation policies reviewed was beyond the scope of our study. However, existing studies highlight that GHG abatement from LDVs can bring considerable savings opportunities via reduced fuel consumption. For example, an analysis for California showed that a range of transportation policies including emissions standards for light- and heavy-duty vehicles would have nominal costs in eight of nine policy approaches of between −\$18 and −\$183 per $MMtCO_2e$ (*43*). For consumers there is a positive net present value over a 15-year vehicle life for purchasing a more efficient car, even with a substantial premium for the efficiency (up to \$1000), and assuming 2008 gasoline prices (\$0.77 L^{-1} [\$3.00 gal^{-1}]) or higher (*18*). Analyses of fuel switching costs are more mixed. The California study showed a savings for an LCFS in that state (*43*), but an assessment of a national LCFS reducing carbon intensities by 10% showed costs of \$80B to \$760B annually, with average costs of \$307 to \$2272 per tCO_2e (*44*). That study did not consider electricity as a potential low-carbon fuel, though recent research emphasizes the importance of doing so (*45, 46*), especially in evaluating biofuels (*47*).

Calculating economic benefits and costs from VKT strategies is difficult. Infrastructure changes may involve multibillion dollar investments for projects spanning many years; valuations of societal shifts in work, housing, and recreational patterns related to transportation modes are complex. Increasing the utilization of existing infrastructure (e.g., carpooling; see first row of Figure 3a) could yield immediate emission reductions at low or negative cost. Beyond the direct benefits and costs, there may be ancillary benefits from GHG reduction policies from the coincident reduction in, e.g., non-GHG pollutants, congestion, and destruction of natural habitat, that are potentially important but difficult to evaluate comprehensively.

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Supporting Information Available

Fleet efficiency assumptions for CAFE and California vehicle standards projections; comparison to vehicle standards for Japan and Australia (SI 1); Low Carbon Fuel Standard scenario assumptions; assumptions for biodiesel consumption (SI 2); heavy-duty on-road vehicle emissions reductions (SI 3); Minnesota transportation data and GHG emissions, 1970−2004 [MS Excel] (SI 4). This material is available free of charge via the Internet at http://pubs.acs.org.

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