

Potentials for Sustainable Transportation in Cities to Alleviate Climate Change Impacts

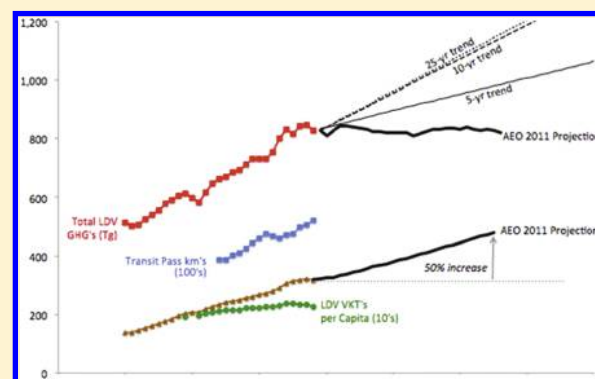
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ABSTRACT: Reducing greenhouse gas emissions (GHG) is an important social goal to mitigate climate change. A common mitigation paradigm is to consider strategy “wedges” that can be applied to different activities to achieve desired GHG reductions. In this policy analysis piece, we consider a wide range of possible strategies to reduce light-duty vehicle GHG emissions, including fuel and vehicle options, low carbon and renewable power, travel demand management and land use changes. We conclude that no one strategy will be sufficient to meet GHG emissions reduction goals to avoid climate change. However, many of these changes have positive combinatorial effects, so the best strategy is to pursue combinations of transportation GHG reduction strategies to meet reduction goals. Agencies need to broaden their agendas to incorporate such combination in their planning.



1. INTRODUCTION

As Charles and Lester Lave noted in 1999: “The automobile has transformed American cities, the economy, and even social interactions. The appeal of mobility, convenience, and affordability have all contributed to an enormous demand for cars and light trucks”.¹ The large U.S. demand for driving has continued and increased in the years since 1999. However, as the Laves were well aware, roadway vehicles are responsible for many negative impacts. Driving results in approximately 10 million accidents and 39 000 deaths each year.² In addition, roadway vehicles cause negative externalities including air pollution costing Americans \$53 billion annually even with extensive emission control systems³ and traffic congestion resulting in 3.9 billion wasted gallons of fuel and 4.8 billion wasted hours of time totaling \$115 billion.⁴ Other negative externalities of driving are petroleum dependence, noise pollution, and urban sprawl.⁵ To achieve sustainable transportation, the U.S. needs to reduce these negative externalities. In this paper, we will focus on strategies to reduce greenhouse gas (GHG) emissions from light duty vehicles (LDV).

Alleviating transportation-related greenhouse gas (GHG) emissions and associated climate change impacts has received less attention than other LDV externalities such as emissions of criteria air pollutants. Yet, any robust GHG mitigation strategies will need to substantially reduce GHGs from LDVs since LDVs represented 65% of U.S. transportation GHGs and 18% of total U.S. GHGs in 2009.⁶ The Intergovernmental Panel on Climate Change (IPCC) estimates that a reduction of 50–85% of global CO₂ emissions below 2000 levels by 2050 is

needed to limit global mean temperature rise to 2.0–2.4 °C.⁷ Baer⁸ estimates that global per capita emissions must be reduced 80% below 2000 levels in the same period. This reduction schedule seems daunting when applied to domestic transportation, particularly given the growth in travel discussed below. Other studies emphasize the challenges of reducing GHG emissions from the transportation sector. For instance a recent Transportation Research Board study⁹ reports that an 8% GHG reduction from the 2030 projection is attainable only if 75% of new developments are built highly dense. A study from the Pew Center for Global Climate Change¹⁰ estimates that aggressive improvements to technology, land use, driver behavior, and transportation management could achieve at best a 40% reduction below 2035 projections. A case study in California, focusing only on in-state emissions, shows that 80% GHG reduction below 1990 levels is possible in California by 2050 only if various strategies and technologies are combined to change travel behavior, vehicles and fuels.¹¹

Despite these challenges and a certain level of pessimism, large reductions in GHG emissions are needed to reduce negative impacts from climate change. The climate change effects in major urban areas are a significant concern; most notable are the effects from sea level rise and coastal acidification that could seriously degrade existing infrastructure

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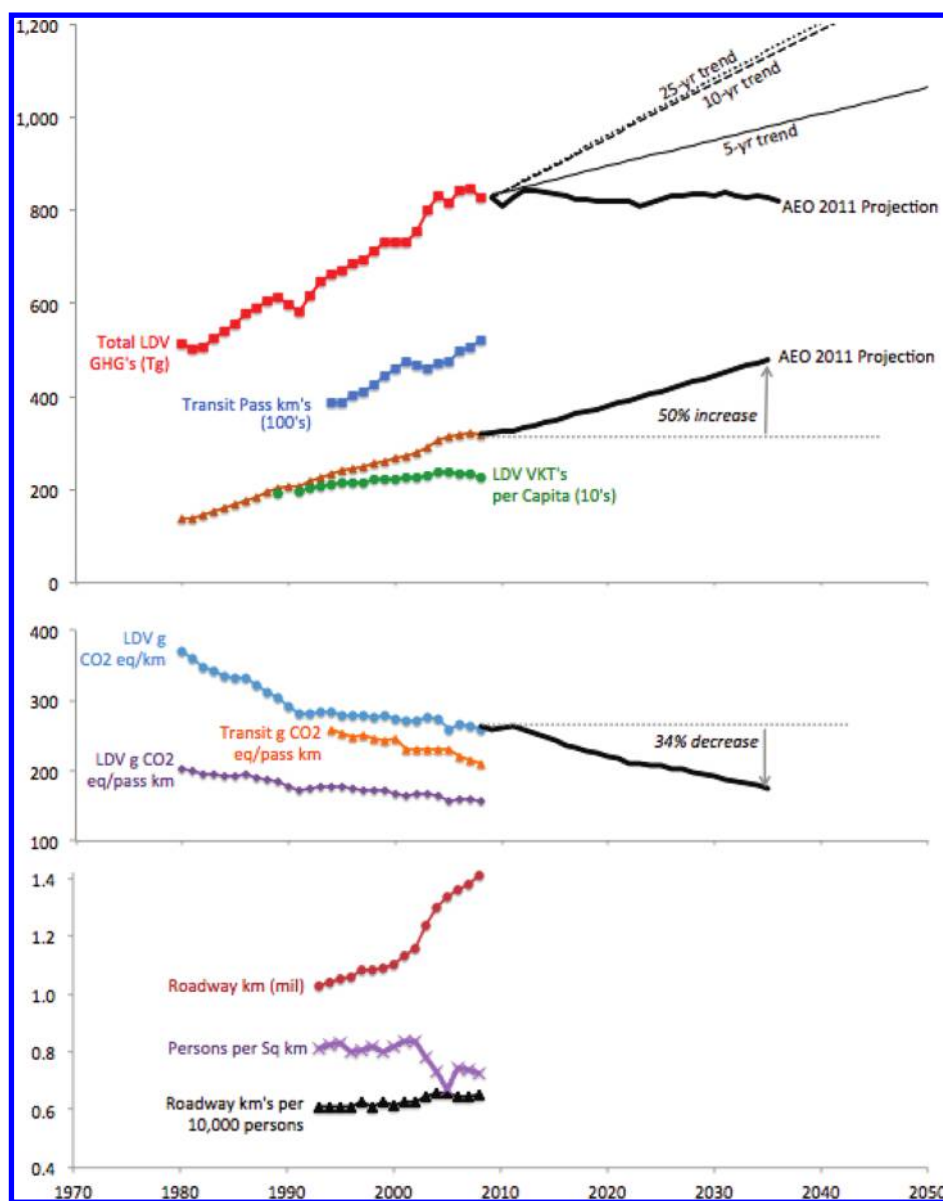


Figure 1. United States light duty vehicle use, greenhouse gas emissions and selected characteristics of density and roadway extent (Source: refs 18–22).

functionality and quality of life in increasingly expanding metropolitan areas. With respect to the U.S. transportation systems, flood events put existing rail, port, and airport operations under significant pressures. Rail lines generally were sited along rivers, coastlines, and low-lying areas more than a hundred years ago and followed available “least cost” paths. Port facilities are built on existing shorelines and would face considerable infrastructure challenges from rising sea levels. Airports are built on large flat plains, and in the case of coastal urban areas, would need significant earthen barriers around them to protect against higher water levels. Cities also need to be concerned about the resilience of their mass transit systems, especially those below ground, in an era of increasing sea levels and potential storm surges. Underground rail transit and tunnel systems have shown to be susceptible to higher water levels and could represent hundreds of billions of dollars of required improvements. The closure of New York City’s subway system due to Tropical Storm Irene is a recent example of the cost due to storm surges.¹² However, few cities are

pursuing strategies that would address climate change impacts. If anything, cities tend to be following “business as usual” patterns by constructing more of the status quo: politicians get re-elected by building roads, not by making existing systems more resilient. Hardoy¹³ cites three reasons for the failure of cities to better prepare: fast-growing cities are overwhelmed in providing for other needs, leaders are under pressure to downplay the need for health and safety standards in order to promote economic growth, and climate projections are rarely detailed enough to predict specific impacts on individual cities.

Given the likely negative effects of climate change that could seriously disrupt our transportation systems, there is a significant opportunity to think and plan better systems that are both resilient and sustainable. We need to reconsider transportation goals, infrastructure systems, and strategies. While rethinking our priorities, we can also implement strategies that reduce GHG emissions. By having systems with less impact, we can potentially spend less on adapting them to the likely effects of climate change.

In this policy analysis paper, we consider a broad range of transportation related strategies to alleviate the effects of climate change impacts and to achieve a goal of 50–80% reduction in GHG emissions from LDV transportation. Our strategies include fuel and vehicle changes, travel demand management, land use planning, and low-carbon power. While many studies have evaluated the potential impact of mitigation strategies in isolation, this study combines a wide range of GHG reduction strategies to prepare reasonable pathways to achieving the 2050 reduction goals. While uncertainty constrains a traditional GHG mitigation analysis using technical and economic feasibility, we use literature data, geographic comparisons, and reasonable assumptions to map various GHG reduction strategies. These strategies then identify primary barriers, critical transitions, and practical considerations to achieving aggressive GHG reductions. Finally, we discuss some of the major costs and benefits associated with achieving the 2050 reduction goal.

We conclude that no one strategy in isolation will be adequate to achieve the 50–80% GHG reduction goals described above, but that combinations of strategies have significant positive impacts for such reductions. This conclusion is consistent with other analyses^{14–16} of the multitude of strategies required to meet overall GHG reduction targets, but our analysis emphasizes the effects of combinations among the different transportation “wedge” strategies.

2. EXISTING AND PROJECTED U.S. LIGHT DUTY VEHICLE TRANSPORTATION EMISSIONS

Future GHG emissions from LDV transportation depend on three critical and uncertain variables: the average fuel consumption of vehicles weighted by use (MJ/km), the life cycle GHG intensity of fuels (g CO₂e/MJ) and overall travel demand (km).^{15,16} It can also be conceptually useful to decompose the travel demand term (km of travel) to reflect population and economic growth: travel demand (km) = km per gross domestic product \times gross domestic product per capita \times population. However, the relationship between marginal increases in GDP and travel demands is not straightforward.

Figure 1 shows historical demand for LDV travel and its associated GHG emissions for the period 1980–2009. Total LDV GHG emissions increased over 60% from 1980 to 2009, primarily due to a more than doubling of travel demand (measured as vehicle kilometers traveled (VKT)). LDV emissions intensity (measured as grams CO₂ eq/VKT) decreased about 30% over the same period due to fuel economy increases.¹⁷ While vehicle efficiency is important to reduce GHG emissions, reducing the demand for personal transportation is equally, if not more, important.

Figure 1 also shows projections through year 2035 of LDV travel demand, emission intensity, and total LDV GHG emissions published in the Energy Information Administration's Annual Energy Outlook (AEO).¹⁸ The AEO projects that LDV travel demand measured as VKT will increase 50% over the next 25 years, which is relatively consistent with long-term historical trends and makes GHG reduction even more difficult.

If long-term historical trends are used to project future emissions, significant increases in LDV emissions can be expected, as shown in Figure 1. Significant reductions in GHG emissions from LDV travel will require major deviations from many, if not all, of the historical trends shown in Figure 1. These trends are driven by increasing demand for passenger travel, decreasing population densities, and increasing roadway

kilometers. The 2011 Annual Energy Outlook, however, projects total LDV GHG emissions to remain near current levels over the next 25 years.¹⁸ Such leveling has been observed over the past few years. This projected emissions leveling is driven primarily by a projected decrease in emissions intensity (measured as g CO₂eq/VKT) of 34% by 2035. While emission intensities are expected to decrease at a rate double what was observed in the 1990s, the projected rate of decrease is consistent with observations in the 1980s. The 1980s experienced aggressive increases in corporate average fuel economy (CAFE) standards, and similar increases to the standards are scheduled over the next decade. While efficiency enhancements and fuel transitions are likely to reduce GHG emissions, as forecasted by EIA, additional significant changes are needed to achieve substantial GHG reductions.

3. FUEL/VEHICLE STRATEGIES

Considerable effort has been devoted to fuel and vehicle strategies to reduce GHG emissions, including several studies by Lester Lave and colleagues.^{1,10,15,23–28} Moreover, federal and state mandates are in place for more fuel-efficient vehicles and for low carbon fuels to replace the current standard gasoline powered internal combustion engine vehicle. Of importance in the near-term will be the combination of the first ever U.S. LDV GHG emissions standard and associated changes in the CAFE standard, requiring a large increase in the average fuel economy of new LDVs (with the proposed standard increasing to 56 mpg by 2025).^{29,30} According to EPA (p. ii), “The fleetwide average adjusted Model Year (MY) 2009 light-duty vehicle fuel economy is 22.4 mpg, an increase of 1.4 mpg since MY2008, and the highest since the database began in 1975”.³¹ While, there are been a gradual increase in fuel economy over the last six years, the U.S. fleet significantly lags those in most other countries with respect to fuel efficiency. Based on the direct relationship between gasoline (or diesel) fuel use and CO₂ emissions, the implementation of fuel efficient vehicle technologies/low carbon fuels combined with motivating consumers to choose these vehicles will be critical for reducing GHG emissions from the US LDV fleet.

With respect to alternative fuels/vehicles, change has been slow due to considerations related to conventional gasoline LDVs as well as those related to the alternative fuel vehicles. Gasoline LDVs are generally viewed as being attractive to consumers with respect to cost and performance metrics. For example, the comparatively low taxes on gasoline in the U.S. compared with those in other countries have not incentivized most consumers to choose smaller, fuel-efficient vehicles or to drive less. The higher cost and/or limited availability of new technologies, unwillingness on the part of consumers to adopt the technologies, and the significant infrastructure changes required to develop and market several advanced fuels and vehicles have also contributed to the limited uptake of alternatives. According to the EIA, in 2009 (most recent data available), 1 076 350 alternative fuel and hybrid vehicles were made available in the U.S., 75% of these were E85 vehicles.³² While vehicle sales overall for 2009 were lower than prior years due to a challenging economy, the numbers presented indicate the relevant trends. In that same year, there were approximately 700 000 alternative fuel LDVs in use compared to 254 million vehicles overall in the LDV fleet. The in use alternative fuel vehicle numbers do not include hybrid electric vehicles or E85 vehicles believed to be in use as traditional gasoline-powered

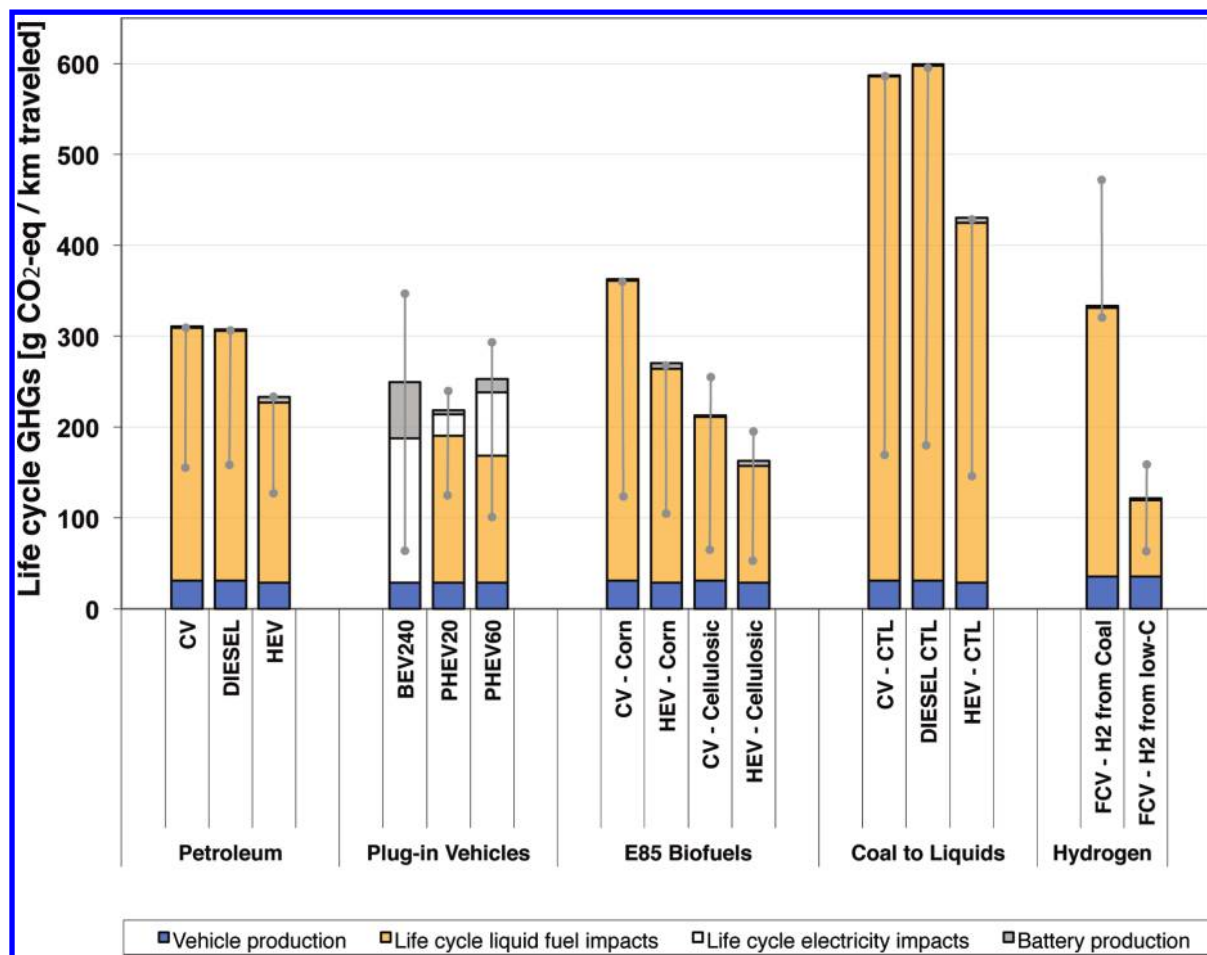


Figure 2. Greenhouse gas emissions per kilometer of travel for various light duty vehicles and fuel combinations (Source: refs 34–38). Error bars denote potential improvements over the next few decades with dramatic increases in vehicle efficiency, use of 200–1000 g CO₂e/kWh electricity, reductions in biofuels impacts, capture and storage of CO₂ during CTL production, H₂ low-carbon electrolysis, and H₂ distribution by truck. Scenarios are not exhaustive and are shown to illustrate the challenges of large GHG reductions from LDVs.

vehicles (as E85 vehicles can be fueled with gasoline or any ethanol/gasoline blend up to 85% ethanol by volume).

Figure 2 illustrates the potential magnitude of GHG reductions from a variety of fuel and vehicle changes relative to a conventional gasoline-fueled LDV (conventional vehicle/CV). Although a number of fuel/vehicle options have potential to make considerable reductions in GHG emissions, none are expected to be able to achieve the 50–80% emissions reduction goal noted above. Widespread adoption of more efficient petroleum-fueled vehicles such as diesels, hybrid electric vehicles (HEV) or advanced CVs can reduce life cycle emissions by approximately 10–20% per kilometer of travel, with dramatic efficiency increases bringing additional reductions. Electrified vehicles can result in larger emissions reductions, but are limited by GHG emissions associated with current electric power generation; effects of low carbon power generation are discussed below. Using biofuels such as E85 (85% ethanol/15% gasoline by volume) could result in increases or reductions in emissions compared to the CV, depending on the feedstock (e.g., corn or cellulosic biomass) and fuel production pathway. While producing ethanol from corn is a mature technology, producing it from cellulosic feedstocks is not yet at commercial scale. The large uncertainties in the biofuel life cycle emissions estimates in Figure 2 are primarily associated with uncertainty in the effects

of land use change that occurs when land previously in other uses is converted to produce a biofuel feedstock.³³ Using coal as a feedstock to produce gasoline and/or diesel through the Fischer–Tropsch process results in GHG emission increases.³⁴ Finally, fuel cell vehicles using hydrogen (FCV-H₂), which have technical and economic hurdles to overcome prior to coming to market, only result in GHG reductions if low carbon sources of hydrogen can be obtained in large quantities.³⁴ There are other potential fuel and vehicle technologies under development that are not discussed here (e.g., algae biodiesel). While some of these options offer promise of very low GHG emissions, they are still in the development stage and major uncertainties exist related to technical and economic viability and scale of production.

In sum, fuel and vehicle changes do offer the possibility of reduced life cycle GHG emissions. However, the reductions are unlikely to achieve the national 50–80% goal discussed above. Also, the largest reductions would be expensive and dependent upon development of new technology and supporting infrastructure. Finally, Figure 2 illustrates GHG emissions per km driven, but for any particular fuel/vehicle combination, growth in overall km traveled would result in GHG emission increases as discussed below. Hence, to achieve the required GHG reductions in transportation, dramatically more efficient

vehicles will need to travel fewer kilometers using an energy source with substantially reduced GHG emissions.

4. LOW CARBON AND RENEWABLE POWER STRATEGIES

As mentioned above, vehicle electrification has been identified as a mechanism to support more sustainable transportation systems by potentially reducing GHG emissions, reducing urban pollution, and displacing petroleum fuels. The electrification of the U.S. vehicle fleet could also support a more sustainable energy system by allowing for the large-scale integration of variable and intermittent energy resources. Low-carbon and renewable electricity generation could considerably reduce the life cycle GHG emissions impacts of plug-in vehicles.

Several studies have examined the potential life cycle emissions reductions resulting from a transition to electrified transportation.^{35,39} A 2008 study by Samaras and Meisterling³⁹ reported that using the average U.S. electric grid emission factors, the life cycle GHG emissions of plug-in hybrid vehicles (PHEVs) could be 30% lower than the emissions from conventional gasoline vehicles. If low-carbon or renewable sources of electricity were used, PHEVs could reduce emissions by more than 50% compared to conventional vehicles. A recent study by Michalek et al.³⁵ used economic valuation to estimate the externality costs associated with vehicle operation. Though the analysis includes the valuation of different pollutants at different locations, the economic values they report can be used as a proxy for sustainability benefits that could be obtained through vehicle electrification. The study reports that the externality costs associated with the life cycle air emissions of PHEVs with small battery sizes charged using low-carbon or renewable sources could be as much as \$800 lower than for conventional vehicles. The biggest savings are observed in the reduction of carbon monoxide (CO), small particulate matter (PM_{2.5}), volatile organic compounds (VOCs), and GHGs.

The studies above estimate emission reductions by assuming low-carbon power can always be used to charge vehicles. In reality this is an unlikely scenario for the next few decades. The operations of the electric systems require that demand and supply be balanced instantaneously. In order to do this, a fleet of power plants using different fuels is operating at any given time. Wind and solar resources are intermittent and require changes in the operations of the grid at appreciable generation fractions. Estimating the actual emissions reductions that may result from electric vehicles in a system with large renewable penetration requires an analysis of the system-wide impacts of charging the vehicles that includes charging time considerations and power plant dispatching. Sioshansi and Denholm⁴⁰ used a unit commitment and dispatch model to estimate the emission impacts of PHEVs at different penetration rates (between 1% and 15%). Their paper reports a range of marginal GHG emission factors of 582–935 kg CO₂ eq/MWh. To demonstrate the importance of transitioning to a low-carbon electricity for PHEVs, using the higher GHG value and the vehicle energy use reported in their study, we estimate that the emissions for the PHEV (only including the tailpipe emissions and the emissions at the power plants) at a 15% penetration of wind power could achieve a 13% GHG reduction relative to conventional vehicles.

Other studies have estimated emission impacts of PHEVs (e.g., Peterson et al.⁴¹) However, none of these studies model an electric system with high wind/solar penetration. Though

there is consensus that PHEVs can reduce the GHG emissions associated with transportation, the actual reductions are difficult to estimate and greatly depend on assumptions about time of charging, grid operations, driving patterns, and electricity generation mix. The role that renewable resources will play in these emission reductions is not clearly understood. Certainly, exclusively charging PHEVs with renewable resources would provide the greatest emission reductions. Given the requirements in current grid operations, considerable changes in grid operations are required to realize this scenario.

The previous discussion focused on the role renewable power plays in supporting low-carbon electrification of transportation. The electrification of transportation could also promote sustainable energy systems by supporting the integration of variable and intermittent renewable resources like wind and solar.^{42,43} As previously described, the thermal power plants are generally assumed to provide the power that needs to be available to balance the variability of wind and solar. Using these conventional resources likely increases the costs and decreases the environmental benefits of deploying renewable resources. Ongoing research is identifying other mechanisms to manage this variability. It has been suggested that the batteries in electric vehicles can be used to provide ancillary services to the grid. Vehicle-to-Grid applications seem to have garnered the most interest.⁴⁴ Smart charging of electric vehicles could also support wind and solar integration. Further research is ongoing on the implementation and emissions reduction potential of these strategies.

5. TRAVEL DEMAND MANAGEMENT BENEFITS

Travel demand management (TDM) is the ability to alter travel behavior through strategies and policies that reduce the demand of driving by either reducing trip generation or changing trip distribution. Eliminating trip generation is typically through combining trips or promoting other modes of transportation such as public transit, biking, walking and ridesharing. Improving physical activity and reducing automobile accidents are cobenefits of promoting other modes of transportation. Redistribution of trips is generally achieved through flexible work hours, congestion pricing, cordon pricing, and parking management. Whether it is promoting other modes of transportation to eliminate trips or redistribution of trips, impacts, benefits, costs and timelines can be significantly different from one strategy to another. Thus, in achieving sustainable transportation through demand management strategies, careful consideration to choose the most feasible yet effective strategy or combination of strategies is needed. Furthermore, strategies that reduce congestion may result in increases in traffic demand as travelers perceive less congestion. This rebound effect potentially reduces the benefits of travel demand management measures implemented.

From 1995 to 2008, VKT increased from about 3 trillion to approximately 5 trillion in the U.S., representing an average annual increase of about 2%.²² As shown in Figure 1, VKT is projected to continue to increase at an average annual rate of 1.6% over the next twenty years.⁴⁵ According to the 2009 National Household Travel Survey (NHTS) there are about 210 million licensed drivers and roughly the same number of vehicles in the U.S. These drivers and vehicles were responsible for about 3.8 daily person trips per person, 60 daily person kilometers, three daily vehicle trips, daily vehicle miles traveled of 48 km per driver and an average vehicle trip length of 16 km per trip.⁴⁶

Table 1. Travel Demand Management Measures and Their Characteristics (from ref 47)^a

category	examples	timeframe	impact on GHG reduction	feasibility of effective implementation	cost of implementation	reference
pricing	VKT fees, intercity toll, pay-as-you-drive insurance, congestion pricing, cordon pricing	short-term benefits	low-moderate	low ^b	moderate–high	48–51
transit, nonmotorized and intermodal travel	transit expansion, promotion and improvement, non-motorized transport,	medium term benefits	low-moderate	high	moderate–high	49,52–54
land use and parking	land use, parking management	long-term benefits	low-high	low-moderate	low	9,49,54–57
commute travel reduction	telework, worksite trip reduction programs, ridesharing, carpooling	short-term benefits	low–moderate	moderate–high	low–high	49,58–62
public information campaign	information on travel choices, eco-driving	short to medium term benefits	low-high	high	moderate–high	62,63

^aImpact on GHG reduction column is characterized as low (reductions less or equal to 0.5% of current transportation GHG emissions by 2030), moderate (reductions between 0.5 and 2.5% of current transportation GHG emissions by 2030), and high (emission reductions equal or greater than 2.5% of current GHG emissions by 2030). Low feasibility indicates that either there are very limited applications proven feasible or the strategy is unlikely to gain popularity in the U.S. political arena. Moderate feasibility indicates some pilot tests have been conducted or there are a limited number of implemented projects. High feasibility indicates that the strategy is likely to be accepted by market forces and the only obstacle is funding. Timeframe column indicates the time period it takes for the strategy to get implemented and benefits are seen (i.e. short: few years). The Implementation cost categories are as follows: High cost \geq \$200 per tonne Co₂e reduced, moderate cost = \$20–200 Co₂e reduced and low cost \leq \$20 per tonne Co₂e. ^bWith an exception of pay as you drive insurance which is moderate to high.

Table 1 shows five categories for travel demand management, illustrating measures within each category, time frame to see the benefits of each, actual impact range on GHG emission reduction, feasibility of implementing the measures effectively and literature references.⁴⁷ While some of the TDM strategies have significant impact on GHG emissions, they would still be insufficient on their own to achieve the GHG reduction targets overall.

6. LAND USE STRATEGIES

Of the travel demand management strategies mentioned in Section 5, land use has been receiving significant attention over the last decades. Based on the U.S. Department of Transportation report mentioned above,⁴⁷ land use strategies have low implementation costs while benefits range from moderate to high. In addition, benefits of land use strategies can potentially grow over time. Compact developments, mixed-use developments, pedestrian and bicycle friendly communities, and transit oriented developments are all forms of land use strategy that can reduce travel activity by decreasing trip lengths and number of vehicular trips. Growing Cooler⁵⁵ estimates that compact urban development can reduce vehicle miles traveled (VMT) by 20–40% compared to sprawl. Other studies^{9,64–67} report that compact and infill developments reduce VMT and its associated GHG emissions. Table 2 summarizes travel reduction percentages associated with land use strategies from various studies. Conversely, other studies^{68,69} criticize compact development as the cause of traffic congestion, higher taxes, and more intensive developments.

The NRC recent literature review⁹ on the influence of urban form on transportation demands suggests that density, land use diversity, and urban design alone have modest impacts on travel demands (elasticities less than 7% with an increase in urban feature results in a decrease in travel demand). The combination of these features can have a more significant effect, but still with elasticities generally less than 15%. More significant reductions can be achieved when density, diversity, and design are supplemented with transit access, with elasticities greater than 20%. Some researchers demonstrate a density threshold effect, whereby travel demands are somewhat insensitive to densities above the threshold and highly sensitive

Table 2. Past Studies of Travel and GHG Reductions of Various Types of Developments

study	type of land use	typical travel reduction	GHG and air pollutant reduction
CSI ⁴⁹	compact development	20–60%	20–60%
NRC ⁹	compact development	5–25%	5–25%
Ewing ⁵⁵	compact development	20–40%	18–36%
Litman ⁷¹	smart growth reforms ^a	4–12%	
Mashayekh ⁶⁶	brownfield in-fill development	38–63%	25–75%
EPA ⁷²	brownfield in-fill development	32–57%	32–57%
EPA ⁷³	brownfield in-fill development	14–52%	
Nagengast ⁷⁴	brownfield in-fill development		36%

^aSmart growth promotes land use changes to encourage concentrating of growth in compact, walkable, transit oriented, developments and to limit sprawl.

below. Density thresholds are believed to be necessary to support viable transit, thereby shifting traveler mode choice.⁷⁰

The objective of altering land use patterns to achieve sustainable transportation is to ultimately lower the number of trips and shorten the length of trips. The two objectives can be achieved through implementing and incorporating various design decisions and elements. The following is a list of potential elements and type of developments that can be used while designing a development and altering land use patterns:

- Compact development: higher density results in less travel activity.
- Mixed use development: providing multiple services and types of land use within one area results in less number of trips and shorter length of trips.
- Pedestrian and bicycle friendly development: providing bicycle and pedestrian networks, connectivity, safety and aesthetic environment promotes less travel activity.

- Transit oriented development: close proximity and accessibility to transit services reduces the number of trips.
- Infill/brownfield development: redevelopment of underutilized land in the urban core of the cities reduces travel activity.

While each of the above developments has a potential of lessening carbon intensive travel activity, combining them would result in synergistic impact on VKT reduction. Hence in achieving the maximum reduction in travel activity and its associated GHG emissions, the key is to combine as many possible elements of each of the above-mentioned developments.

Land use strategies can be an effective tool to achieve sustainable transportation. They have a potential of reducing travel activity. They typically incur minimal cost to the regional and federal transportation authorities and metropolitan planning organization as most of their cost is paid by private entities and mainly developers. Public agencies can provide incentives and guidelines to ensure the design implementation of smart growth and land use elements that would result in higher vehicular travel reduction. Incentives can be provided so that developers are encouraged to develop those sites that are in close proximity of transit and other service areas. Moreover, guidelines can be enforced for the design of walkable streets, connectivity factors, safety and aesthetic elements, and higher density of developments. Through effective collaboration between public agencies and private developers not only travel activity and its associated GHG emissions is reduced but cobenefits such as increased physical activity, less number of accidents, increased transit ridership are expected. Moreover, land use changes can be directed at areas that would not be affected by sea level change. One disadvantage for land use changes is that they only take effect over long period of time as only small changes in land uses typically occur annually.

7. DISCUSSION

The above synthesis suggested that a single transportation strategy would not be sufficient to achieve substantial transportation GHG reductions. However, combinations of these strategies are possible. Moreover, transportation strategies are not individual wedges to reduce pollution but can be mutually reinforcing.

None of the strategy categories alone are likely to have greater than a moderate impact on GHG emissions. However, each of the strategies can have significant reinforcing effects with other strategies. For example, vehicle electrification complements renewable power (by reducing emissions per kilometer), travel demand management and land use changes (by reducing the amount of travel and thereby avoiding range constraints with battery electric vehicle or gasoline driving with plug-in hybrid electric vehicle). Similarly, travel demand management can be more effective with land use changes to achieve a more compact and walkable metropolitan area. In our judgment, the GHG reduction potential taking advantage of these different complementary effects is high. GHG emission reduction goals could be attained by aggressively pursuing both existing policies and the four strategies discussed here: fuel/vehicle strategies, travel demand management, land use change, and renewable power.

Strategies exist to support reductions of GHG emissions from personal transportation. We propose that two concepts

are fundamental for implementing these strategies and achieving more sustainable transportation systems that align with the emission reductions needed to lessen the impacts of climate change.

- (1) Strategy Combination Impact: while each measure and strategy has a potential of lowering VKT and GHG emissions, it is the combination of various strategies or development types (in the case of land use) that results in maximum impact. Combining various types of development (i.e., transit oriented, pedestrian friendly, compact, and infill) results in the greater VMT reduction than focusing on only one type of land use. Focusing just on vehicle changes would miss the opportunities for renewable power and land use effects.
- (2) Agencies Collaboration: to successfully move toward sustainable transportation, cooperation and collaboration between public agencies on local, state and regional levels as well as between public and private entities is crucial. The goal should be to create platforms, tools and processes that enhance this collaboration and to make decisions more effectively.

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DEDICATION

This paper is dedicated to Lester B. Lave.

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