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Abstract: In recent years, there has been increasing focus on creating policy to achieve deep reductions in global greenhouse gas (GHG) emissions, particularly the 80% GHG reduction goal by 2050 recommended by the IPCC and proposed in the Paris Agreement. In this study, we produce a suite of scenarios that project GHG emissions from the light-duty and heavy-duty vehicle fleet in the Michigan transportation sector in 2050. This analysis focuses on the effectiveness of the aggressive adoption of battery electric vehicles, hydrogen fuel cell vehicles, biofuels, and advanced internal combustion engines and hybrid vehicles on deep emission reduction goals. We estimate tailpipe and upstream emissions produced by the comprehensive adoption of these technology pathways and for promising combinations. Results indicate that none of the single strategy solutions will be capable of reducing Michigan's transportation sector emissions by 80% by 2050, and combinations of technological solutions cannot reach this goal without aggressive GHG management in upstream sectors. This research highlights the potential abilities and limitations of proposed technological solutions to bring about deep net GHG emissions reductions in Michigan's transportation sector.

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Highlights

- We explore vehicle technology adoption scenarios in Michigan by 2050.
- Projected emissions in 2050 are compared to aggressive emissions reduction goals.
- Single-strategy vehicle technology solutions are unable to reach desired reductions.
- Upstream emissions sources are a challenge for adoption of alternative fuel vehicles.
- Deep reductions are unlikely to occur if vehicle travel demand continues to increase.

Title page

Evaluating Technology Pathways for Achieving an 80% Reduction in the Light-Duty and Heavy-Duty Fleet Emissions for the State of Michigan

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Abstract. In recent years, there has been increasing focus on creating policy to achieve deep reductions in global greenhouse gas (GHG) emissions, particularly the 80% GHG reduction goal by 2050 recommended by the IPCC and proposed in the Paris Agreement. In this study, we produce a suite of scenarios that project GHG emissions from the light-duty and heavy-duty vehicle fleet in the Michigan transportation sector in 2050. This analysis focuses on the effectiveness of the aggressive adoption of battery electric vehicles, hydrogen fuel cell vehicles, biofuels, and advanced internal combustion engines and hybrid vehicles on deep emission reduction goals. We estimate tailpipe and upstream emissions produced by the comprehensive adoption of these technology pathways and for promising combinations. Results indicate that none of the single strategy solutions will be capable of reducing Michigan's transportation sector emissions by 80% by 2050, and combinations of technological solutions cannot reach this goal without aggressive GHG management in upstream sectors. This research highlights the potential abilities and limitations of proposed technological solutions to bring about deep net GHG emissions reductions in Michigan's transportation sector.

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1. Introduction

As global atmospheric concentrations of carbon dioxide (CO_2) continue to increase, finding effective strategies to curtail global greenhouse gas (GHG) emissions is of paramount importance. The United States and other developed countries must reduce their total GHG emissions by 80% by 2050 relative to 2005 levels as part of the Paris Agreement. Such deep reductions will be necessary to limit global temperature increases to 2 degrees Celsius over pre-industrial levels (Solomon 2007). Across all sectors of the economy, this will require substantial changes, and the ways in which sectors respond to this challenge must necessarily differ and will require coordinated local and regional action.

Early in 2016, CO_2 emissions from the transportation sector in the United States exceeded those of electricity generation for the first time since the late 1970s (EIA 2016a). That the transportation sector has become the leading source of CO_2 emissions in the United States is a result of a combination of technological, economic, and policy-driven factors. There has been a nearly 25% reduction in emissions from the nation's electricity generation sector from 2008 to 2016, largely due to a decrease in the use of coal for power generation and a corresponding increase in the use of natural gas (EIA 2016b). In spite of continued increases in the fuel economy of the national light-duty vehicle fleet since 2004 (EPA 2016a), CO_2 emissions in the transportation sector are increasing, and beginning to approach their pre-recession levels, largely driven by continued growth in vehicle miles traveled (VMT) nationwide (FHWA 2016a). Globally, transportation emissions represent a substantial share of anthropogenic GHG emissions (Schaefer et al. 2009, Unger et al. 2009). Emissions from the transportation sector, then, are important to address when considering GHG mitigation strategies, but there is not widespread agreement on how best to proceed.

Traditionally, recommendations to reduce GHGs in the transportation sector center on three general pathways: 1) reduction of travel demand, 2) improvement of vehicle efficiency, and 3) transitions to so-called low-carbon fuels, with particular emphasis on the latter two (e.g., Melaina and Webster 2011). The latter two pathways are technological, where deep reductions are sought through advances in vehicle and fuel technologies, while the former is dependent on changes in the many infrastructure, financial and geographic determinants of travel. Using this traditional framework of transportation emissions as a "three-legged stool," varying degrees of transportation sector GHG reductions can be modeled by constructing scenarios defined by assumptions about technological pathways for alternative fuel vehicle (AFV) adoption, and fuel economy gains, augmented by travel demand reductions.

Technological options are appealing from a policy standpoint because they allow transportation systems to continue to operate without drastic changes in travel behavior, though their ability to do so may be more limited than is traditionally thought. Achieving deep GHG reductions in the transportation sector ultimately requires deep reductions in net GHG emissions from sectors that supply transportation energy (DeCicco 2013; NAS 2013). These findings indicate that aggressive adoption of a particular vehicle-fuel technological pathway, referred to as a "silver bullet," will have limited success, and may be unproductive given the uncertainties in the GHG reduction trajectories of other sectors. While there is growing consensus that no silver bullet exists that can achieve the desired deep reductions (McCollum and Yang 2009; Grimes-Casey et al. 2009), technology-based solutions deployed in combination remain, at least in some political circles, popular suggestions for achieving deep reductions. The White House (2016) Mid-Century Strategy to help reach an 80% reduction in economy-wide emissions specifically mentions the adoption of electric vehicles and biofuels as promising pathways. An understanding of the abilities and limitations of technological solutions to bring about deep reductions is central, then, to effective policy recommendations for the transportation sector.

McCollum and Yang (2009) and Yang et al. (2009) conducted such an assessment, modeling ways to achieve an 80% reduction in transportation sector emissions by 2050 for both the nation and for the state of California. Using a modification of the Kaya (1990) framework, they found that combinations of technical strategies could approach the desired levels of deep reductions, but that travel demand management would be necessary to reach 80%. Olabisi et al. 2009 find that the state of Minnesota can achieve 80% GHG reduction across all sectors through nearly complete decarbonization of the electricity and transportation sectors, but this study did not specifically focus on transportation.

These studies illustrate some of the potential capabilities and limitations of technological pathways and their ability to provide deep reductions in the transportation sector, but the ability to translate results from these limited studies is uncertain. First, it is useful to consider economic sectors separately from a policy implementation standpoint, as different agencies or branches of agencies are responsible for creating policy in these areas. Secondly, the variation across state or regional economic activity, travel behavior, and electricity generation is important to consider when recommending technological solutions. In this study, we consider the state of Michigan, which differs from California (Yang et al. 2009) in a number of ways that affect transportation emissions. Michigan has an electricity grid far more reliant upon coal than that of California, and its economic activity, climate and travel behavior differ. Perhaps more importantly, California has a number of policies and incentives that support emission reductions in the transportation sector that Michigan currently lacks. In these ways, Michigan becomes more representative of a state or region in the United States outside of California that faces the challenge of finding ways to address rising GHG emissions without strong political support. Limited research has considered how to achieve deep reductions in Michigan's transportation sector, or a state similar to it.

Therefore, this paper explores the ability of vehicle-fuel technology solutions to reach the 80% GHG emissions reduction objective by 2050 in the state of Michigan's transportation sector. The research question is: to what extent can aggressive adoption of technological solutions, such as advanced vehicle technology and alternative fuel vehicles, either singularly or in combination, reduce GHG emissions in the state of Michigan by 2050? While it is true that not each state and economic sector must individually reduce their emissions by 80%, they must in aggregate, and Michigan's transportation sector may be an important bellwether for assessing how viable many of the proposed solutions to reduce emissions from the national transportation sector may be at the state or regional level.

We also consider emissions from both the light and heavy-duty vehicle fleets in our analysis. Though both types of travel are quite different, each must be considered in a comprehensive policy that reduces emissions in the transportation sector at the state or regional level. In 2014, heavy-duty vehicles accounted for 4% of the national vehicle fleet in the United States while producing about 29% of the GHGs in the national transportation sector (FHWA, 2015; EPAb, 2016), so strategies must consider these differing magnitudes of impacts. Given Michigan's location as a port-of-entry for the movement of goods between the United States in Canada, this is of particular importance to a statewide strategy.

2. Methodology

The forecast of CO_2 emissions in the state's transportation sector includes a number of projections, including those for travel demand growth, ratios and volumes of light and heavy-duty vehicles in the state's transportation fleets, vehicle fuel economy, and the rate of technology adoption and implementation in the statewide vehicle fleet.

2.1 Technology Pathways

The particular technology pathways explored in this analysis are: 1) high efficiency internal combustion engines and hybrids that continue to operate with liquid petroleum fuels, 2) battery electric vehicles (BEVs), 3) hydrogen fuel cell vehicles (HFCVs), and 4) internal combustion engines that operate with liquid biofuels. For each of these scenarios, we consider comprehensive adoption of each vehicle technology in the statewide fleet by 2050, and we do not consider external factors such as market shocks, geopolitical interventions, or rebound effects while modeling the scenarios. This is similar to the approach of McCollum and Yang (2009). We also do not attempt to analyze AFV infrastructure barriers, assuming that establishing the infrastructure necessary to support an AFV technology is part of the pathway. Neither do we analyze customer acceptance issues regarding range, capacity or convenience issues for different vehicle types. Thus, these scenarios merely assess the extent to which hypothetical technological solutions can bring about deep emissions reductions without assuming any significant changes in personal and freight travel patterns.

2.2 Projections of Vehicle Travel

We estimate the VMT change for Michigan's transportation sector using the most recent national estimate, which is as a compound annual growth rate of 0.8% per year through 2050 (EIA 2017). This national estimate includes both light- and heavy-duty vehicles. In 2013, heavy-duty vehicle travel represented 9.6% of Michigan's VMT (MDOT 2016), and is expected to rise to 14% by 2050, so we incorporate this updated share in each scenario (see Appendix B). In each case, we assume a consistent rate of VMT growth in order to produce a consistent comparison of vehicle technology pathways. We do acknowledge that VMT reduction strategies, including travel demand management or land use changes, could alter these outcomes, but we do not consider those here in order to determine the relative effectiveness of the technology pathways.

2.3 Fuel Economy

Fuel economy estimates for vehicles sold between 2035 and 2040 are used to model 2050 emissions projections, allowing for a more realistic appraisal of the vehicle fleet (Table 1). We also consider the balance of light-duty trucks and light-duty cars in these estimates. The source of 2050 fuel economy estimates is the National Academy of Sciences (2013) report, which considered a variety of light-duty vehicle types that may be operating by 2050. We then converted each of these estimates to on-road fuel economy values. The NAS 2013 report produced two separate fuel economy values for light duty vehicles by 2035-2040: one entitled "Midrange," and one called "Optimistic." The Midrange values represent the NAS committee's best assessment of 2050 fuel economy, considering potential costs and reasonable technological performance relative to today's standards, while the Optimistic values are "best case" scenarios that represent the absolute maximum performance of a future technology that may be feasible with aggressive advances in technology and lower manufacturing and production costs. We consider each of these scenarios separately for the Michigan light-duty vehicle fleet in 2050.

For heavy-duty vehicles, we projected 2050 heavy-duty fuel economy estimates as a result of implementing the EPA's Phase 2 standards. These estimates consider the improvements in vehicle classes 4-6 and 7-8 (EIA 2016e).

2.4 Emissions Estimates

The estimates of fuel consumption and associated GHG emissions consider projected VMT for the state of Michigan in 2050, along with vehicle fuel economy and fuel type. The combination of these factors create energy demand vectors both in the transportation sector and other sectors that meet transportation energy demand, which vary based on the technological pathway of interest. Within the transportation sector, we partition tailpipe emissions into those produced by both light- and heavy-duty vehicle travel. We then project upstream emissions in external economic sectors (EPA, 2016c; EIA, 2015). Upstream sectors include the electricity generation sector, hydrogen production, and gasoline and diesel fuel production, and for liquid biofuels, include land use changes, feedstock production, and fuel production. The varied nature of these upstream sectors present unique challenges for GHG mitigation efforts.

For Michigan's electricity generation sector, we estimate upstream emissions in 2050 using a combination of projected electricity generation volumes combined with Clean Power Plan implementation benchmarks (EPA, 2016d), along with a continued decrease in carbon intensity in the grid until 2050 (see Appendix A). For the HFCV scenario, we first consider the production method for hydrogen. Currently, steam reformation with natural gas as an energy source is the primary means by which hydrogen is produced, with the remainder through electrolysis. Emissions generated through the latter method are create upstream emissions in the electricity generation sector.

Emission factors for the fuels and energy carriers in this study are defined in terms of grams of CO_2 per gallon, kWh or kg of fuel use. Once projected fuel demand for each scenario and vehicle-fuel technology type has been calculated (Eq. 1), emissions are estimated as a product of fuel use and emissions factors (Eq. 2).

$$Fuel\ Demand_i = VMT_i / Fuel\ Economy_i \qquad (1)$$

where: i represents the vehicle type in the scenario and where fuel is gallons of liquid fuel by type (gasoline, diesel, biofuel), kWh of electricity or kg hydrogen (Table 2).

$$\sum Emissions = \sum (Fuel\ Demand\ x\ Emission\ Factor) \quad (2)$$

3. Results and Scenarios

We present a series of seven scenarios to estimate future CO_2 emissions as result of Michigan's transportation activity by 2050, comparing projections to the desired 80% reduction from 2005 levels. The combination of the lower bound of the projected fuel economy values for the light-duty fleet and those for the heavy-duty fleet for each sector in Table 1 represents the "Low" version of each of the following scenarios. The "High" version of each scenario is the combination of the upper bound of both the light- and heavy-duty vehicle sectors.

3.1 Scenario A - Reference Scenario

The Reference scenario assumes that petroleum fuels continue to be used for transportation at market shares little changed from present-day use. The existing CAFE Standards continue to help improve the fuel economy of the light-duty fleet, while the heavy-duty fleet becomes more efficient due to hybridization. The conservative version of the scenario assumes that fuel economy standards are relaxed and the fleet fuel economy in 2050 is close to the new vehicle fuel economy in 2014. In the optimistic version of this scenario, there is a 24% decrease in total emissions from 2005 levels (Figure 1, Table 3). The upstream sector affected by this scenario would be that of gasoline and diesel fuel production, where the energy demand requirement would produce an additional 8.4 to 11.9 MMT of CO_2.

This scenario would represent an improvement in emissions reductions, but would not reach 80%. Increasing VMT offsets emissions reductions gained through improved fuel economy. The CO_2 tailpipe emissions per mile reduces for the light duty fleet from 399 gCO_2/mile in 2005 to 163 gCO_2/mile in 2050, while the heavy-duty fleet emissions reduce from 1540 gCO_2/mile in 2005 to 1118 gCO_2/mile in 2050 in the optimistic scenario.

3.2 Single Strategy Aggressive Implementation Scenarios

Four scenarios evaluate emissions that would result from a comprehensive adoption of a single technology pathway in the Michigan transportation sector by 2050. These include: 1) adoption of aggressive fuel economy standards beyond existing ones, with continued use of petroleum-based fuels for transportation, 2) adoption of battery electric vehicles (BEVs), 3) adoption of hydrogen fuel cell vehicles (HFCVs), and adoption of vehicles that operate using liquid biofuels.

3.2.1 Scenario B - Advanced IC Engines and Hybrids Scenario

In contrast to the reference scenario, this projection includes more optimistic projections about both future engine technology for vehicles in Michigan by 2050. These fuel economy values should be interpreted as representations of the upper limits of plausible technological advancements in engine technology given present-day technologies, with uncertainty as to precisely how far fuel economy advances will progress by 2050 constrained by the midrange and optimistic fuel economy values provided in the NAS 2013 report. Contained within this scenario is an assumption that there is a much higher degree of hybridization of the powertrain for all vehicle types, which could substantially reduce total fuel use. If all plausible advances in engine technology are realized by 2050, total emissions from Michigan's transportation sector could decrease by 28-57% compared to 2005 levels. In the most optimistic scenario, tailpipe emissions could lower to 97 gCO_2/mile for light duty vehicles and 595 gCO_2/mile for heavy duty vehicles. In this case, the upstream sector impacted is that of gasoline and diesel fuel production, creating additional emissions ranging between 4.7-8.0 MMT of CO_2.

3.2.2 Scenario C - Electric Vehicles

In this scenario, we assume that the entire light-duty vehicle fleet transitions to BEVs, and that 35% of the heavy-duty fleet does as well. The remaining portion of heavy-duty fleet vehicles continues to operate using diesel fuel, and to a lesser extent, gasoline. This represents an aggressive BEV adoption rate in the heavy-duty vehicle fleet, which is likely to avoid comprehensive adoption of BEVs due to the nature of their travel.

Electric vehicles have no tailpipe emissions, so all impacts are concentrated in the upstream electricity generation sector. This makes the source of electricity central to any projection of GHG emissions in this scenario. If coal continues to be the leading source of electricity generation in the state, even the most optimistic fuel economy projection for BEVs would generate more than 200 gCO_2/mile for light-duty vehicles upstream. In contrast, upstream emissions could be minimal if carbon-free electricity sources are used. These represent the extreme cases of electricity generation sources, which are unlikely to occur in the future. To continue the focus on vehicle technology solutions in the transportation sector, we estimate future emissions in the electricity sector by assuming that the state's power plants continue to implement the Clean Power Plan until 2030, with reductions of 2% per year continuing from 2030 until 2050 (see Appendix A). In this case, upstream emissions are 376 gCO2 per kWh delivered, and we assume that the additional generating capacity demand required to satisfy vehicle travel is satisfied.

There are no tailpipe emissions produced by the light-duty vehicle fleet and 730 gCO_2/mile produced by the heavy-duty vehicle fleet. A transition to a full BEV light-duty vehicle fleet would incur upstream emissions of 90 gCO_2/mile for light-duty travel and 444 gCO_2/mile for heavy-duty vehicle travel. Of note, on the optimistic end of the scenario, it is possible to achieve an 80% reduction in CO_2 emissions in Michigan's transportation sector, although the upstream emissions produced would make the total emissions roughly equivalent to that of the optimistic version of the Advanced IC Engines and Hybrids Scenario. In total, this scenario leads to an overall decrease in emissions by 41-57% when accounting for both tailpipe and upstream emissions, relative to 2005.

3.2.3 Scenario D - Hydrogen Fuel Cell Vehicles

In this scenario, all vehicle travel is completed using hydrogen, as it could conceivably be used by all classifications of vehicles. As is the case with BEVs, there are no tailpipe CO_2 emissions from HFCVs. Upstream emissions do occur, and depend on the production method for hydrogen. At present, the majority of hydrogen (about 90%) is produced through steam reformation of methane (SMR) or the light oil fraction with steam at high temperatures (Haryanto, 2005), but hydrogen can also be produced by electrolysis of water.

For the purposes of transportation, using hydrogen produced through electrolysis is less efficient than the way in which BEVs directly use electricity. Hydrogen production through electrolysis is electricity intensive and incurs significant losses in the process. Like the BEV scenario, upstream emissions in this scenario are dependent on the source of the electricity used to produce hydrogen, if electrolysis is employed. Hydrogen could be produced by electrolysis using purely carbon-free electricity sources, but the use of the state's grid-based electricity would incur higher upstream emissions values. Similar to the BEV scenario, a transition to HFCVs with hydrogen production through electrolysis would necessitate additional electrical power generation in the state. This study assumes a combination of 90% SMR and 10% electrolysis for hydrogen production, which is consistent with current hydrogen production.

The HFCV scenario leads to a complete removal of tailpipe CO_2 emissions in the transportation sector, but it does produce upstream emissions equivalent to 40-60% of 2005 transportation emissions, depending on fuel economy improvements. When considering upstream emissions in hydrogen production and electricity generation, comprehensive adoption of HFCVs will not meet the 80% emission reduction goal.

3.2.4 Biofuels

The incorporation of biofuels into the state's transportation sector carries more uncertainties and complexities than the previous scenarios. Here, "biofuels" are considered to be liquid energy carriers which are derived from biomass feedstocks. The extent to which production of those feedstocks increases the net rate of CO_2 removal from the atmosphere determines the extent to which biofuels will help mitigate emissions from the transportation sector (DeCicco, 2015). In this scenario, we assume that all vehicle travel in all sectors is completed using liquid biofuels. Agricultural, forestry and land-use management practices will determine the extent of the upstream offsets and careful carbon accounting is necessary to ensure offset integrity.

A distinction of biofuels compared to the other fuels is that the feedstock used to produce biofuel removes CO_2 from the atmosphere. In the United States, corn ethanol is the most common form of biofuel that is available as a liquid fuel, and corn is one of the more productive crop types relative to carbon uptake. It is commonly assumed that the CO_2 uptake from the biomass used to produce liquid biofuels completely offsets the biogenic CO_2 emitted during both the biofuel production and at the tailpipe. However, recent research is critical of this assumption (DeCicco 2012, 2015). Biofuel feedstock production may offset some of the biogenic CO2 emitted during biofuel production and combustion. Here we estimate the magnitude of the offsets needed based on biofuel demand and the amount of net fuel supply sector GHG reduction needed to reach the overall 80% reduction target in 2050.

As a result of this high degree of uncertainty, we do not estimate a single emission factor value for biofuels (Figure 2). We have considered offsets ranging from around 80% offset from gasoline emissions to an increase of 40% from gasoline emissions due to upstream processes, including feedstock production, fuel production, and land use changes. The fuel economy is also dependent on the type of biofuel used and vehicle engine parameters. The current blend of "gasoline" sold already includes a blend of 10% ethanol (E10), which has a lower fuel economy compared to pure gasoline, which is what present-day engines are designed to use. If the biofuel blend percentage increases or if a large-scale shift occurs from fossil fuels to biofuels, engines could be designed in a way that optimizes fuel economy for biofuels. We have considered fuel economy ranging from a decrease by 15% to an increase by 25% from the Reference scenario's optimistic fuel economy.

Figure 2 demonstrates that a number of combinations can achieve an 80% emission reduction relative to 2005. Even with no fuel economy change relative to Reference scenario's optimistic fuel economy, biofuels would require to have offsets of around 70% from gasoline emissions to reach the 80% target.

3.3 Combination Scenarios

The results from the single strategy scenarios demonstrate the challenge in relying upon the implementation of a singular vehicle-technology pathway to achieve deep reductions in the Michigan transportation sector by 2050. In the case of the BEV and HFCV scenarios, an 80% reduction within the transportation sector is possible, but when considering upstream emissions, none approaches the desired level. In this section, we present the ways in which combinations of technological solutions and additional measures could achieve 80% emission reductions, highlighting the difficulty of meeting the desired goal.

The presented scenarios target an 80% emissions reduction, working backwards to reach the goal, which differs from our analysis of the single technology strategies. The two combination scenarios are closely related: the first scenario allocates 60% of the light-duty VMT to BEVs, with the remaining 40% of the VMT to vehicles that operate with liquid biofuels. The second scenario allocates 80% of the light-duty VMT to BEVs and 20% to biofuels. In each of those two scenarios, the heavy-duty fleet VMT is 20% BEVs and 80% of the VMT belongs to vehicles that operate with liquid biofuels.

In the case of electricity generation, moving towards more carbon-free electricity sources is one way to remove upstream emissions from BEVs. For all emissions, increased carbon uptake through land management practices has the ability to remove CO_2 from the atmosphere generated by any source. Figure 3 accounts for the potential to achieve an 80% reduction relative to 2005 emissions through these two upstream emissions reductions pathways. An offset of 0% is equivalent to the average combined tailpipe and upstream emissions of diesel and gasoline, which is about 11 kg CO_2/gallon.

An electricity grid that is completely reliant on coal generates 984 gCO_2/kWh (EIA 2016d). As a point of reference, Michigan's present-day electricity sector represents a 39% reduction of this value and we project that it will reach 62% by 2050. Even with this improvement, Figure 3 shows that substantial offsets would be required to reach the 80% reduction goal through either combination scenario, even with aggressive decarbonization of Michigan's electricity grid. Notably, if the grid becomes entirely devoid of carbon emissions, a 44%

upstream emissions offset would be still required to achieve the 80% reduction in the 80:20 combination scenario, with a 53% offset necessary in the 60:40 combination scenario. Note that these offset percentages signify the reductions per gallon of fuel or per kWh of electricity used.

We find that when considering upstream emissions and the potential to offset them, it is possible that adoption of electric vehicles and biofuels in Michigan by 2050 could help to reach an 80% reduction, though the additional actions in the transportation energy supply sectors are not trivial.

4. Discussion

The aggressive single-strategy implementation scenarios illustrate how improvements in vehicle engine technology or singular comprehensive adoptions of any type of alternative fuel vehicle will alter the emissions produced by Michigan's transportation sector by 2050. It is unlikely, though, that any of these scenarios will represent the state's vehicle fleet composition in 2050, as both light and heavy duty vehicles will operate with some combination of the fuels and technologies considered in this study, in addition to others not considered here.

In this analysis, we do not propose specific additional actions that would be required beyond the technological solutions to achieve deep reductions. Outside of the offsets and carbon reduction in the electricity grid mentioned in the combination scenarios, these general actions could also include carbon capture and sequestration and a reduction in vehicle travel. The ability for carbon capture and sequestration to operate at a national scale and at the levels needed to bring about deep reductions is very uncertain. There is greater consensus that a reduction in total vehicle travel will also be necessary to reach emissions reduction goals. There are a host of methods available to regional planners and city and state governments that could be applied, including those broadly identified through travel demand management, land use changes and mixed-use development, and it will fall to local governments to implement those strategies to bring about meaningful reductions in state VMT. In this study, we assume a compound growth rate of VMT consistent with Annual Energy Outlook 2017 (EIA 2017) and historical trends dating to the 1970s. It is possible that the trend may change in the future due to policy or market intervention, but that is unlikely, given that the rate of change in VMT was only interrupted by the Great Recession and has continued to climb again at historical rates since that point. This is indicative of the challenges involved in reducing VMT at large geographic scales. Our research shows that to reach 80% reduction target, even for optimistic fuel economy projections, VMT would have to decrease drastically by as much as 50%-55%, relative to the 2050 Reference VMT projections.

There is also uncertainty in the rate at which supporting technologies, including hydrogen production, battery manufacturing for electric vehicles, energy sources for the electricity grid, and Smart Grid construction will evolve, which could all influence the way in which the technologies considered in this paper advance. Future market trends and disruptions, variations in infrastructure development, and continuing advances in connected and automated vehicles all could affect the rate at which alternative fuel vehicles are introduced to the market at the scales assumed in this paper. Connected and automated vehicles, in particular, may also have a substantial impact on VMT, but the nature and magnitude of this change is uncertain. We do not consider the variations in investment, construction, and manufacturing needed to allow widespread adoption of these vehicle technologies to occur relative to today, nor do we directly incorporate market competition between vehicle manufacturers when constructing any scenario that includes alternative fuels. All of these factors will almost certainly influence the future composition of the vehicle fleet, but trying to account for this involves a high degree of uncertainty, and obscures analysis of the technological capabilities and limitations of the strategies included in this study.

Finally, we present emissions volumes that result from each scenario as an aggregate of tailpipe and upstream emissions, and it is important to consider the changes in tailpipe and upstream emissions separately from a policy standpoint. Regulations and oversight may differ both across and within federal agencies responsible for enacting emissions standards. For example, the Office of Transportation and Air Quality within the Environmental Protection Agency can set standards for vehicle tailpipe emissions, and while the agency can set standards by which electricity generation stations should abide under the Clean Air Act, states determine how best to meet those standards for stationary sources within their boundaries. This distinction in the way in which regulations are implemented in these sectors is important to consider when making recommendations about GHG reductions relative to Michigan's transportation activity.

5. Conclusion

Results from this analysis indicate that comprehensive adoption of either very high efficiency internal combustion engines or alternative fuel vehicles will not alone be sufficient for Michigan's transportation sector to reduce its GHG emissions by 80% by 2050. While tailpipe emissions could be reduced to an almost negligible amount with complete transitions to HFCVs or BEVs, the already-high burdens placed upon other sectors to reduce their emissions would be increased substantially as a result of these transitions. Popular technological solutions to the transportation emissions problem can achieve reductions to a degree, but fall short of the important 80% reduction benchmark, and even in combination, cannot do so without substantial changes in other economic sectors.

Further research focused on ways to reduce aggregate local VMT, which in turn will help reduce that of a state like Michigan, is also needed. While this study does not recommend specific strategies to reduce vehicle travel in Michigan, it does illustrate that any strategy to reduce travel demand must consider both light and heavy-duty vehicle travel, given the projected share of emissions from heavy-duty vehicle travel by 2050. Many of the recognized strategies in the urban and transportation planning literature are focused on the former, but by 2050, reductions in heavy-duty vehicle travel may be an important area of emphasis as its relative share of projected VMT increases.

Transportation and electricity generation are the two largest contributors to CO_2 emissions at present at the national scale, and the interaction between the two must be considered when crafting effective policy that can lead to deep GHG emission reductions in the transportation sector by 2050. In our analysis, a combination of electric vehicle adoption and biofuel use in both the light- and heavy-duty vehicle fleet, performs better than any of the single-strategy solutions at achieving deep emission reductions in the transportation sector in Michigan, but only if coupled with a high percentage of largely carbon-free power generation in the electric sector and high levels of CO_2 removal offsets in the land-use sector. That means it is possible to achieve the desired emissions reduction levels, though such a strategy would require a significant increase in electrical generation from zero- or very-low GHG emitting technologies, which is likely to face financial and political barriers. There is also little existing regulatory framework for the production of offsets at the scales required, which is an important area of future research. Strategies to bring about deep CO_2 emissions in Michigan's transportation sector must recognize complex interactions between economic sectors, regulatory agencies, and travel behavior, and must avoid the temptation to propose single technology strategies.

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Table 1 Fuel Economy Ranges

	Fuel Economy (mpgge)		
Vehicle Type	Light Duty Cars[a]	Light Duty Trucks[a]	Heavy Duty Trucks[b]
IC Engines and Hybrids - Reference	36-53	26-40	7-9
Advanced IC Engines and Hybrids	52-91	37-64	7-18
Electric	142-155	99-117	15-16
Hydrogen	100-120	70-84	11-15

[a] Lower end of fuel economy range equivalent to "Midrange" values (NAS 2013), converted to on-road fuel economy, with higher end equivalent to "Optimistic" values, also converted to on-road fuel economy
[b] Estimates for heavy-duty fuel economy from Phase 2 Standards (EIA 2016e)

Table(s)

Table 2. Emission Factor Table

Fuel	Tailpipe Emission Factor[a]	Upstream Emission Factor[b]
Gasoline (E10)	8.02 kg/gal	1.76 kg/gal
Diesel	10.15 kg/gal	2.23 kg/gal
Electricity (2050)	0 kg/kWh	0.38 kg/kWh delivered
Hydrogen (2050)	0 kg/kg H2	12.78 kg/kg H2

[a]From EIA (2016f)

[b]Estimated values for upstream gasoline and diesel emissions. See Appendix A for electricity values. We assume a 9:1 ratio of SMR to electricity for hydrogen production

Table(s)

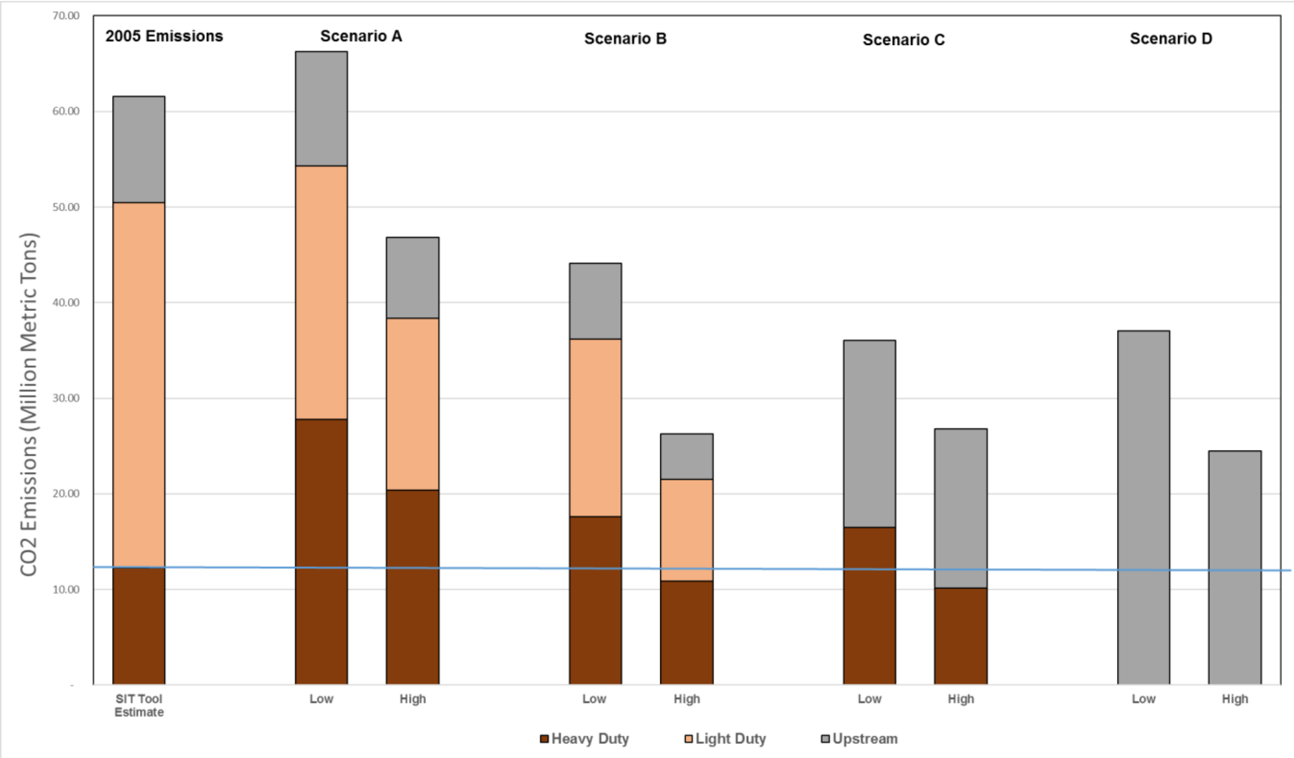
Table 3. Tailpipe and upstream CO_2 Emissions for light duty and heavy duty vehicles for low fuel economy and high fuel economy scenarios (million metric tons CO_2)

	Low Fuel Economy					High Fuel Economy					
Scenario	**HD Tailpipe**	**LD Tailpipe**	**Upstream**	**Total**	**Additional Emissions Reductions Needed**	**HD Tailpipe**	**LD Tailpipe**	**Upstream**	**Total**	**Additional Emissions Reductions Needed**	**Upstream Sectors**
A	27.8	26.5	11.9	66.2	53.9	20.4	18.0	8.4	46.8	34.5	Gasoline and Diesel Well-to-Pump
B	17.6	18.5	8.0	44.1	31.8	10.9	10.7	4.7	26.3	13.9	Gasoline and Diesel Well-to-Pump
C	16.5	0.00	19.6	36.1	23.8	10.2	0.00	16.6	26.8	14.5	Gasoline and Diesel Well-to-Pump, Electricity Generation and Distribution
D	0.00	0.00	37.0	37.0	24.7	0.00	0.00	24.5	24.5	12.2	Hydrogen Production

Table 4. Range of tailpipe and upstream emissions per mile for each scenario.

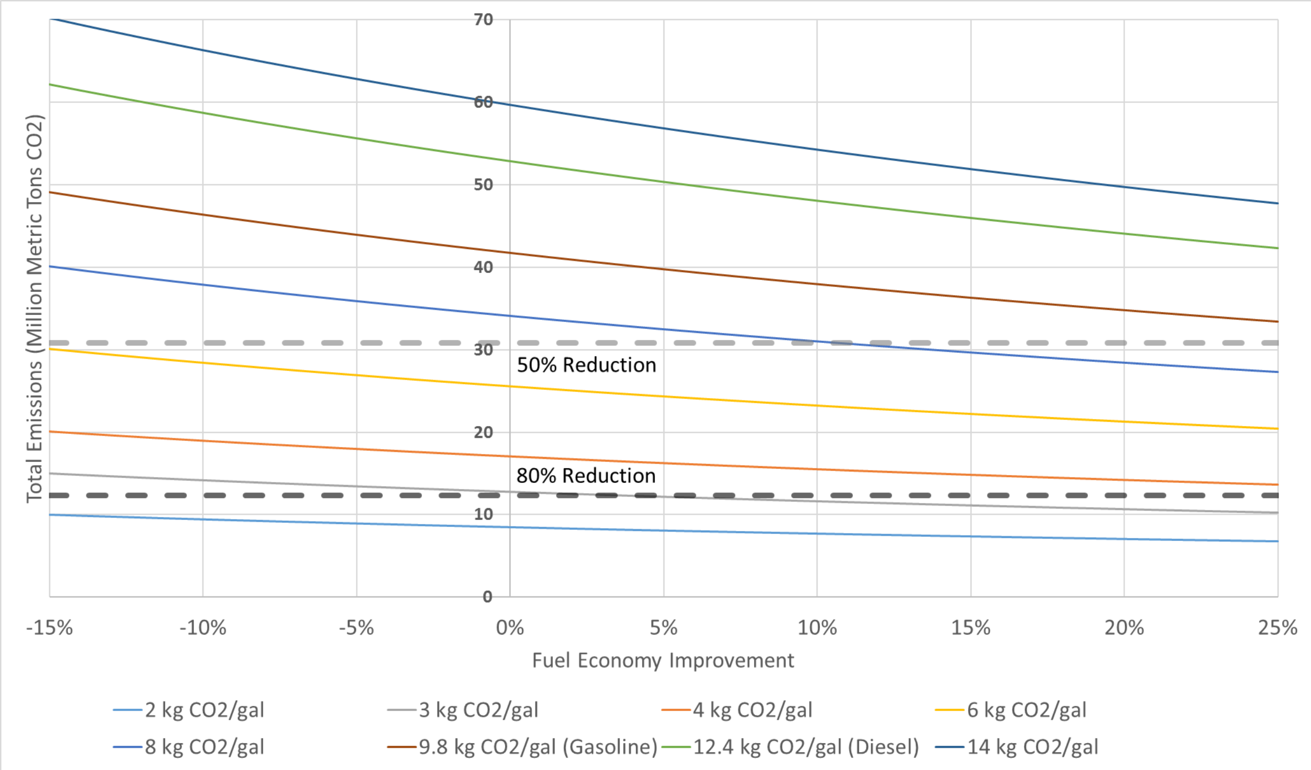
Scenario	Tailpipe Emissions (HD) (gCO_2/mile)	Upstream Emissions (HD) (gCO_2/mile)	Tailpipe Emissions (LD) (gCO_2/mile)	Upstream Emissions (LD) (gCO_2/mile)
A	1118-1523	246-335	163-240	36-53
B	595-965	131-212	97-168	21-37
C	557-903	406-482	0	83-98
D	0	638-1180	0	117-140

Figure(s)



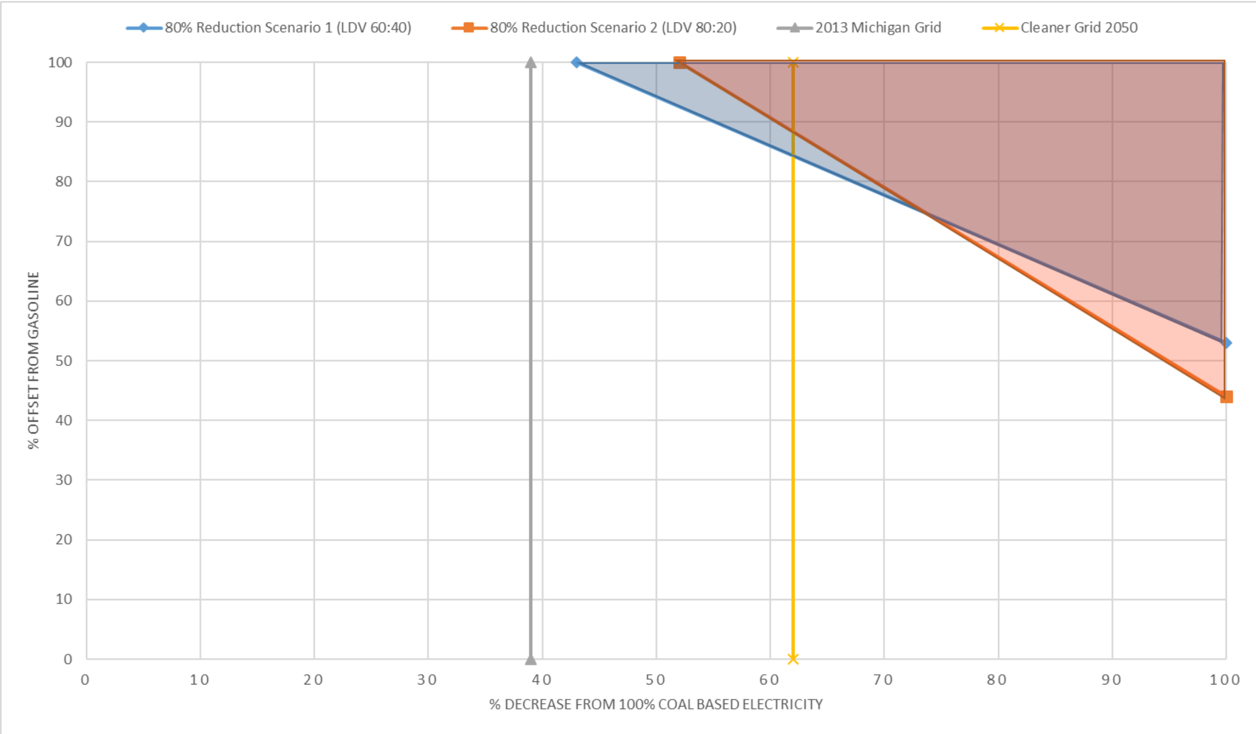
70.00
60.00
50.00
40.00
30.00
20.00
10.00
-
CO2 Emissions (Million Metric Tons)
2005 Emissions
Scenario A
Scenario B
Scenario C
Scenario D
SIT Tool Estimate
Low
High
Low
High
Low
High
Low
High
Heavy Duty
Light Duty
Upstream

Figure(s)



70
60
50
40
30
20
10
0
Total Emissions (Million Metric Tons CO2)
50% Reduction
80% Reduction
-15%
-10%
-5%
0%
5%
10%
15%
20%
25%
Fuel Economy Improvement
2 kg CO2/gal
3 kg CO2/gal
4 kg CO2/gal
6 kg CO2/gal
8 kg CO2/gal
9.8 kg CO2/gal (Gasoline)
12.4 kg CO2/gal (Diesel)
14 kg CO2/gal

Figure(s)



80% Reduction Scenario 1 (LDV 60:40)
80% Reduction Scenario 2 (LDV 80:20)
2013 Michigan Grid
Cleaner Grid 2050
% OFFSET FROM GASOLINE
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
% DECREASE FROM 100% COAL BASED ELECTRICITY

Figure(s)

Figure 1. CO_2 emissions estimates by 2050 across four different scenarios for light duty and heavy duty vehicles, including the reference scenario and the three single-strategy technology implementation scenarios.   Emissions from Michigan's light-duty and heavy-duty emissions for 2005 are provided as a reference from EPA (2016c). The 80% reduction target is the blue horizontal line. Scenario A represents 'Reference 2050 Scenario', Scenario B represents 'Advanced IC Engines and Hybrids Scenario', Scenario C represents 'Electric Vehicles Scenario' and Scenario D represents 'Hydrogen Vehicles Scenario'

Figure 2. Total emissions for the biofuel scenario depending on the change in fuel economy and the total of tailpipe and upstream emissions of the biofuel or blend used. As the fuel economy and emissions per gallon are highly variable there are many combinations that may achieve emission reductions. The grey and black dashed lines represent the 50% and 80% emission reduction level relative to 2005.

Figure 3. After implementation of the two combination scenarios, the shaded area represents the combination of offsets and/or decrease in CO_2 emissions from the electricity sector needed to achieve 80% reductions. The grey line indicates the present-day electricity grid's emissions relative to one of 100% coal, and the yellow line indicates projected Michigan electricity grid emissions after implementation of the Clean Power Plan by 2050.

Supplementary Material

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Supplementary Material
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