# Supporting Information

## Optimizing U.S. Transportation Mitigation Strategies: What We Learn from a Bottom-up Model

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**Summary:** 16 pages, 4 figures, and 6 tables.

Our study uses the EPA national MARKet ALlocation (MARKAL) technology database *(1)*. The model documentation can be downloaded at http://oaspub.epa.gov/eims/eimsapi.dispdetail?deid=150883. The database that we used for this paper was subsequently modified by the International Resources Group for the Natural Resources Defense Council (NRDC) *(2, 3)* and incorporates a series of transportation updates, including the vehicle technology assumptions largely based on the 2007 Annual Energy Outlook *(4)*, improved biomass resource supply curves and biofuel characterization *(5-9)*, and the new ethanol requirement under the Energy Independence and Security Act.

This Supporting Information has two sections. Section S1 describes major assumptions in vehicle types, costs, efficiencies, and emission factors. Section S2 shows additional modeling results not shown in the paper, including projected $CO_2$ emission for all scenarios, cumulative $CO_2$ emission reductions, $CO_2$ mitigation costs, and the calculations for the transportation $CO_2$ emission mitigations from fuel $CO_2$ intensity reduction, vehicle efficiency improvement, and reduction in vehicle miles traveled.

## Section S1. Key model assumptions

*Vehicle costs, efficiency, and emissions*

Table S1 lists the assumptions of the cost of light-duty passenger vehicles. The data sources include the Annual Energy Outlook (AEO) 2006 *(10)* and the Annual Energy Outlook (AEO) 2007 *(4)*, with authors' modification based on literature reviews. Empty cells signify that the technologies are assumed to be unavailable for the given years.

**Table S1.** Cost of light-duty passenger vehicles (thousands of 2000 dollars)

| Size | Type | Abbreviation | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Compact | Adv GSL | C.AGSL | 19.76 | 20.68 | 20.92 | 21.12 | 21.27 | 21.33 | 21.33 | 21.33 | 21.33 | 21.33 |
| Compact | CNG | C.CNG | 24.88 | 25.81 | 26.08 | 26.30 | 26.48 | 26.57 | 26.57 | 26.57 | 26.57 | 26.57 |
| Compact | CNG Flex Fuel | C.CNGX | 23.79 | 24.75 | 25.03 | 25.28 | 25.47 | 25.59 | 25.59 | 25.59 | 25.59 | 25.59 |
| Compact | DSL HEV | C.DHEV | | 24.87 | 25.17 | 25.42 | 25.61 | 25.69 | 25.69 | 25.69 | 25.69 | 25.69 |
| Compact | DSL | C.DSL | 20.12 | 20.93 | 21.08 | 21.20 | 21.29 | 21.32 | 21.32 | 21.32 | 21.32 | 21.32 |
| Compact | Ethanol Flex Fuel | C.ETHX | 19.48 | 20.67 | 20.86 | 21.07 | 21.20 | 21.23 | 21.23 | 21.23 | 21.23 | 21.23 |
| Compact | Fuel Cell - Hydrogen | C.FCH | 68.18 | 60.50 | 53.84 | 49.08 | 44.94 | 41.80 | 41.80 | 41.80 | 41.80 | 41.80 |
| Compact | Conventional | C.GSL | 18.93 | 19.85 | 20.09 | 20.29 | 20.44 | 20.50 | 20.50 | 20.50 | 20.50 | 20.50 |
| Compact | HEV | C.HEV | 22.05 | 22.11 | 21.96 | 21.89 | 21.96 | 21.97 | 21.97 | 21.97 | 21.97 | 21.97 |
| Compact | LPG Flex Fuel | C.LPGX | 23.27 | 24.16 | 24.47 | 24.71 | 24.89 | 24.97 | 24.97 | 24.97 | 24.97 | 24.97 |
| Compact | PHEV | C.PHEV | | | 29.75 | 28.34 | 26.99 | 27.07 | 27.07 | 27.07 | 27.07 | 27.07 |
| Full Size | Adv GSL | F.AGSL | 27.42 | 28.33 | 28.60 | 28.82 | 28.97 | 29.03 | 29.03 | 29.03 | 29.03 | 29.03 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Full Size | CNG | F.CNG | 37.89 | 38.64 | 38.88 | 39.11 | 39.29 | 39.39 | 39.39 | 39.39 | 39.39 | 39.39 |
| Full Size | CNG Flex Fuel | F.CNGX | 36.98 | 37.67 | 37.95 | 38.21 | 38.41 | 38.51 | 38.51 | 38.51 | 38.51 | 38.51 |
| Full Size | DSL HEV | F.DHEV | | | 33.10 | 33.35 | 33.61 | 33.83 | 33.83 | 33.83 | 33.83 | 33.83 |
| Full Size | DSL | F.DSL | 26.62 | 29.15 | 29.32 | 29.44 | 29.50 | 29.51 | 29.51 | 29.51 | 29.51 | 29.51 |
| Full Size | Ethanol | F.ETH | 26.88 | 27.81 | 28.05 | 28.24 | 28.37 | 28.41 | 28.41 | 28.41 | 28.41 | 28.41 |
| Full Size | Ethanol Flex Fuel | F.ETHX | 25.15 | 27.84 | 28.11 | 28.33 | 28.48 | 28.53 | 28.53 | 28.53 | 28.53 | 28.53 |
| Full Size | Fuel Cell - Gasoline | F.FCG | | 100.39 | 86.80 | 76.17 | 76.00 | 75.86 | 75.86 | 75.86 | 75.86 | 75.86 |
| Full Size | Fuel Cell - Hydrogen | F.FCH | | | 63.91 | 60.41 | 55.51 | 51.78 | 51.78 | 51.78 | 51.78 | 51.78 |
| Full Size | Conventional | F.GSL | 26.59 | 27.51 | 27.77 | 27.99 | 28.14 | 28.20 | 28.20 | 28.20 | 28.20 | 28.20 |
| Full Size | HEV | F.HEV | 28.21 | 29.61 | 29.44 | 29.56 | 29.64 | 29.67 | 29.67 | 29.67 | 29.67 | 29.67 |
| Full Size | LPG Flex Fuel | F.LPGX | 31.12 | 31.97 | 32.29 | 32.55 | 32.73 | 32.80 | 32.80 | 32.80 | 32.80 | 32.80 |
| Full Size | Methanol Flex Fuel | F.MTHX | 27.05 | 27.98 | 28.24 | 28.44 | 28.58 | 28.62 | 28.62 | 28.62 | 28.62 | 28.62 |
| Full Size | PHEV | F.PHEV | | | | 38.00 | 36.19 | 36.27 | 36.27 | 36.27 | 36.27 | 36.27 |
| SUV-Large | Adv GSL | LS.AGSL | 35.19 | 36.40 | 36.70 | 36.99 | 37.21 | 37.29 | 37.29 | 37.29 | 37.29 | 37.29 |
| SUV-Large | DSL HEV | LS.DHEV | | | | 43.40 | 43.54 | 43.65 | 43.65 | 43.65 | 43.65 | 43.65 |
| SUV-Large | DSL | LS.DSL | 35.30 | 36.38 | 36.61 | 36.85 | 37.07 | 37.18 | 37.18 | 37.18 | 37.18 | 37.18 |
| SUV-Large | Ethanol Flex Fuel | LS.ETHX | 34.23 | 35.45 | 35.73 | 36.01 | 36.20 | 36.28 | 36.28 | 36.28 | 36.28 | 36.28 |
| SUV-Large | Fuel Cell - Hydrogen | LS.FCH | | | | | 73.90 | 68.09 | 68.09 | 68.09 | 68.09 | 68.09 |
| SUV-Large | Conventional | LS.GSL | 33.89 | 35.11 | 35.41 | 35.70 | 35.92 | 36.00 | 36.00 | 36.00 | 36.00 | 36.00 |
| SUV-Large | HEV | LS.HEV | 38.58 | 38.43 | 38.06 | 38.23 | 38.42 | 38.53 | 38.53 | 38.53 | 38.53 | 38.53 |
| SUV-Large | PHEV | LS.PHEV | | | | | 42.99 | 43.07 | 43.07 | 43.07 | 43.07 | 43.07 |
| Minivan | Adv GSL | M.AGSL | 24.28 | 25.40 | 25.66 | 25.94 | 26.18 | 26.28 | 26.28 | 26.28 | 26.28 | 26.28 |
| Minivan | CNG | M.CNG | 27.86 | 28.96 | 29.23 | 29.52 | 29.79 | 29.93 | 29.93 | 29.93 | 29.93 | 29.93 |
| Minivan | CNG Flex Fuel | M.CNGX | 27.07 | 28.17 | 28.44 | 28.73 | 29.02 | 29.17 | 29.17 | 29.17 | 29.17 | 29.17 |
| Minivan | DSL HEV | M.DHEV | | | 34.22 | 34.36 | 34.51 | 34.61 | 34.61 | 34.61 | 34.61 | 34.61 |
| Minivan | DSL | M.DSL | 23.36 | 26.07 | 26.14 | 26.26 | 26.40 | 26.47 | 26.47 | 26.47 | 26.47 | 26.47 |
| Minivan | Ethanol Flex Fuel | M.ETHX | 24.50 | 25.27 | 25.51 | 25.75 | 25.95 | 26.01 | 26.01 | 26.01 | 26.01 | 26.01 |
| Minivan | Fuel Cell - Gasoline | M.FCG | | | 90.47 | 78.15 | 77.93 | 77.75 | 77.75 | 77.75 | 77.75 | 77.75 |
| Minivan | Fuel Cell - Hydrogen | M.FCH | | | 72.83 | 65.41 | 59.18 | 54.45 | 54.45 | 54.45 | 54.45 | 54.45 |
| Minivan | Conventional | M.GSL | 22.99 | 24.11 | 24.37 | 24.64 | 24.88 | 24.99 | 24.99 | 24.99 | 24.99 | 24.99 |
| Minivan | HEV | M.HEV | | 32.50 | 28.45 | 27.96 | 27.92 | 27.84 | 27.84 | 27.84 | 27.84 | 27.84 |
| Minivan | LPG | M.LPG | 27.22 | 28.35 | 28.60 | 28.86 | 29.08 | 29.18 | 29.18 | 29.18 | 29.18 | 29.18 |
| Minivan | LPG Flex Fuel | M.LPGX | 26.17 | 27.30 | 27.57 | 27.87 | 28.13 | 28.25 | 28.25 | 28.25 | 28.25 | 28.25 |
| Minivan | PHEV | M.PHEV | | | | | 31.95 | 32.05 | 32.05 | 32.05 | 32.05 | 32.05 |
| Mini Compact | Adv GSL | MC.AGSL | 48.06 | 49.00 | 49.22 | 49.38 | 49.52 | 49.56 | 49.56 | 49.56 | 49.56 | 49.56 |
| Mini Compact | Electric | MC.ELC | 64.92 | 65.08 | 63.63 | 63.65 | 63.61 | 63.60 | 63.60 | 63.60 | 63.60 | 63.60 |
| Mini Compact | Conventional | MC.GSL | 47.23 | 48.17 | 48.39 | 48.55 | 48.69 | 48.73 | 48.73 | 48.73 | 48.73 | 48.73 |
| Mini Compact | HEV | MC.HEV | 47.07 | 47.38 | 47.23 | 47.36 | 47.48 | 47.53 | 47.53 | 47.53 | 47.53 | 47.53 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pickup | Adv GSL | P.AGSL | 24.26 | 25.49 | 25.79 | 26.07 | 26.26 | 26.31 | 26.31 | 26.31 | 26.31 | 26.31 |
| Pickup | CNG | P.CNG | 30.16 | 31.35 | 31.67 | 31.98 | 32.22 | 32.33 | 32.33 | 32.33 | 32.33 | 32.33 |
| Pickup | CNG Flex Fuel | P.CNGX | 29.38 | 30.61 | 30.92 | 31.24 | 31.50 | 31.60 | 31.60 | 31.60 | 31.60 | 31.60 |
| Pickup | DSL | P.DSL | 25.34 | 25.65 | 25.89 | 26.08 | 26.22 | 26.28 | 26.28 | 26.28 | 26.28 | 26.28 |
| Pickup | Ethanol Flex Fuel | P.ETHX | 24.09 | 25.30 | 25.54 | 25.76 | 25.87 | 25.86 | 25.86 | 25.86 | 25.86 | 25.86 |
| Pickup | Conventional | P.GSL | 22.96 | 24.20 | 24.50 | 24.77 | 24.97 | 25.02 | 25.02 | 25.02 | 25.02 | 25.02 |
| Pickup | HEV | P.HEV | | 29.62 | 29.02 | 28.42 | 28.32 | 28.11 | 28.11 | 28.11 | 28.11 | 28.11 |
| Pickup | LPG | P.LPG | 29.50 | 30.73 | 31.02 | 31.29 | 31.47 | 31.51 | 31.51 | 31.51 | 31.51 | 31.51 |
| Pickup | LPG Flex Fuel | P.LPGX | 28.46 | 29.71 | 30.03 | 30.34 | 30.57 | 30.65 | 30.65 | 30.65 | 30.65 | 30.65 |
| Pickup | PHEV | P.PHEV | | | | | 32.04 | 32.09 | 32.09 | 32.09 | 32.09 | 32.09 |
| SUV-Small | Adv GSL | SS.AGSL | 27.32 | 28.54 | 28.81 | 29.06 | 29.26 | 29.33 | 29.33 | 29.33 | 29.33 | 29.33 |
| SUV-Small | DSL HEV | SS.DHEV | | | | 35.27 | 35.36 | 35.43 | 35.43 | 35.43 | 35.43 | 35.43 |
| SUV-Small | DSL | SS.DSL | 27.99 | 28.96 | 29.19 | 29.40 | 29.58 | 29.67 | 29.67 | 29.67 | 29.67 | 29.67 |
| SUV-Small | Electric | SS.ELC | 51.53 | 51.55 | 49.82 | 49.89 | 49.85 | 49.82 | 49.82 | 49.82 | 49.82 | 49.82 |
| SUV-Small | Ethanol Flex Fuel | SS.ETHX | | 27.49 | 27.78 | 28.04 | 28.25 | 28.32 | 28.32 | 28.32 | 28.32 | 28.32 |
| SUV-Small | Fuel Cell - Gasoline | SS.FCG | | | 87.27 | 75.78 | 75.59 | 75.44 | 75.44 | 75.44 | 75.44 | 75.44 |
| SUV-Small | Fuel Cell - Hydrogen | SS.FCH | 89.72 | 78.71 | 69.88 | 62.96 | 57.17 | 52.76 | 52.76 | 52.76 | 52.76 | 52.76 |
| SUV-Small | Conventional | SS.GSL | 26.03 | 27.25 | 27.52 | 27.77 | 27.97 | 28.04 | 28.04 | 28.04 | 28.04 | 28.04 |
| SUV-Small | HEV | SS.HEV | | 29.79 | 29.56 | 29.72 | 29.86 | 29.92 | 29.92 | 29.92 | 29.92 | 29.92 |
| SUV-Small | PHEV | SS.PHEV | | | | | 35.04 | 35.11 | 35.11 | 35.11 | 35.11 | 35.11 |

Adv GSL: advanced gasoline vehicles; HEV: hybrid electric vehicles; PHEV: plug-in hybrid electric vehicles. DSL: diesel vehicles; CNG: dedicated natural gas vehicles; LPG: liquefied petroleum gas vehicles

Table S2 lists the assumptions for light-duty passenger-vehicle efficiency (in miles per gallon). These unadjusted values will need to be adjusted for degradation factors, which convert the unadjusted fuel economy to actual "on the road" fuel economy that takes into account three factors: increases in city/highway driving, increasing congestion levels, and rising highway speeds. Sources for Table S2 include the AEO 2006 *(10)*, the AEO 2007 *(4)*, and the DOE's Multi-Path Transportation Futures Study *(11, 12)*, with authors' modification based on literature reviews. Efficiency improvement after 2040 is 2% every 5 yrs. A cell with a value in Table S2 but no corresponding value in Table S1 signifies that the type of vehicle is not available for the given year. Table S3 shows the degradation factors after modification based on the NEMS Transportation Demand Module, Table 28 *(13)*. Compared with the NEMS assumptions, the degradation factors are higher (indicating less degradation) in order to account for the more stringent requirement of the new CAFE standard on vehicle efficiency that may not be sufficiently reflected in Table S2.

**Table S2.** Efficiency of light-duty passenger vehicles (in miles per gasoline gallon equivalent, mpgge).

| Size | Type | Abbrev. | Unadjusted | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 |
| Compact | Adv GSL | C.AGSL | 36.01 | 39.59 | 40.45 | 41.03 | 42.05 | 42.62 | 43.47 | 44.34 |
| Compact | CNG | C.CNG | 34.35 | 37.16 | 39.15 | 39.40 | 40.01 | 40.35 | 41.15 | 41.98 |
| Compact | CNG Flex Fuel | C.CNGX | 31.86 | 34.70 | 36.27 | 36.47 | 37.03 | 37.32 | 38.06 | 38.82 |
| Compact | DSL HEV | C.DHEV | | 39.23 | 43.13 | 44.07 | 44.70 | 45.82 | 46.74 | 47.67 |
| Compact | DSL | C.DSL | 42.53 | 43.72 | 46.03 | 46.13 | 46.62 | 46.97 | 47.91 | 48.87 |
| Compact | Ethanol Flex Fuel | C.ETHX | 32.23 | 34.08 | 35.05 | 35.92 | 37.02 | 37.60 | 38.35 | 39.11 |
| Compact | Fuel Cell - Hydrogen | C.FCH | 58.34 | 57.48 | 61.21 | 67.88 | 71.05 | 77.09 | 78.63 | 80.20 |
| Compact | Conventional | C.GSL | 31.31 | 34.42 | 35.17 | 35.68 | 36.57 | 37.06 | 37.80 | 38.56 |
| Compact | HEV | C.HEV | 45.72 | 46.44 | 51.43 | 54.92 | 57.40 | 62.11 | 63.35 | 64.61 |
| Compact | LPG Flex Fuel | C.LPGX | 31.70 | 34.00 | 35.83 | 36.25 | 37.03 | 37.45 | 38.20 | 38.96 |
| Compact | PHEV | C.PHEV | | | 73.53 | 77.21 | 81.07 | 85.12 | 86.82 | 88.56 |
| Full Size | Adv GSL | F.AGSL | 31.56 | 34.05 | 34.98 | 35.61 | 36.59 | 37.12 | 37.87 | 38.62 |
| Full Size | CNG | F.CNG | 28.47 | 29.78 | 31.70 | 32.16 | 32.91 | 33.37 | 34.04 | 34.72 |
| Full Size | CNG Flex Fuel | F.CNGX | 26.32 | 27.21 | 28.90 | 29.49 | 30.37 | 30.82 | 31.43 | 32.06 |
| Full Size | DSL HEV | F.DHEV | | | 47.58 | 47.62 | 48.17 | 48.64 | 49.61 | 50.60 |
| Full Size | DSL | F.DSL | 37.26 | 37.44 | 39.22 | 39.45 | 40.03 | 40.43 | 41.24 | 42.06 |
| Full Size | Ethanol | F.ETH | 28.86 | 31.26 | 33.07 | 33.64 | 34.52 | 35.02 | 35.72 | 36.44 |
| Full Size | Ethanol Flex Fuel | F.ETHX | 37.50 | 29.73 | 31.47 | 32.04 | 32.91 | 33.42 | 34.09 | 34.77 |
| Full Size | Fuel Cell - Gasoline | F.FCG | | 40.42 | 43.19 | 46.22 | 48.37 | 52.52 | 53.57 | 54.64 |
| Full Size | Fuel Cell - Hydrogen | F.FCH | | | 54.79 | 57.45 | 60.12 | 65.24 | 66.54 | 67.87 |
| Full Size | Conventional | F.GSL | 27.44 | 29.61 | 30.42 | 30.96 | 31.81 | 32.28 | 32.93 | 33.58 |
| Full Size | HEV | F.HEV | 40.09 | 39.63 | 43.66 | 46.73 | 48.99 | 53.12 | 54.18 | 55.26 |
| Full Size | LPG Flex Fuel | F.LPGX | 27.32 | 28.83 | 30.49 | 31.08 | 31.93 | 32.36 | 33.01 | 33.67 |
| Full Size | Methanol Flex Fuel | F.MTHX | 28.33 | 30.70 | 32.45 | 33.00 | 33.86 | 34.36 | 35.04 | 35.75 |
| Full Size | PHEV | F.PHEV | | | 79.10 | 79.10 | 83.05 | 87.20 | 88.95 | 90.73 |
| SUV-Large | Adv GSL | LS.AGSL | 22.65 | 24.49 | 25.71 | 26.50 | 27.53 | 28.22 | 28.79 | 29.36 |
| SUV-Large | DSL HEV | LS.DHEV | | | | 35.15 | 35.66 | 36.30 | 37.03 | 37.77 |
| SUV-Large | DSL | LS.DSL | 25.72 | 27.05 | 27.85 | 28.22 | 29.01 | 29.53 | 30.13 | 30.73 |
| SUV-Large | Ethanol Flex Fuel | LS.ETHX | 19.28 | 20.99 | 22.15 | 22.84 | 23.72 | 24.33 | 24.81 | 25.31 |
| SUV-Large | Fuel Cell - Hydrogen | LS.FCH | | | | | 39.31 | 42.69 | 43.55 | 44.42 |
| SUV-Large | Conventional | LS.GSL | 19.36 | 20.93 | 21.98 | 22.65 | 23.53 | 24.12 | 24.61 | 25.10 |
| SUV-Large | HEV | LS.HEV | 27.81 | 28.06 | 30.29 | 32.63 | 34.62 | 37.84 | 38.59 | 39.36 |
| SUV-Large | PHEV | LS.PHEV | | | 43.97 | 43.97 | 43.97 | 48.05 | 49.01 | 49.99 |
| Minivan | Adv GSL | M.AGSL | 30.04 | 32.18 | 33.56 | 34.27 | 35.47 | 36.26 | 36.99 | 37.73 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Minivan | CNG | M.CNG | 27.93 | 29.57 | 30.76 | 31.21 | 32.11 | 32.70 | 33.35 | 34.02 |
| Minivan | CNG Flex Fuel | M.CNGX | 25.33 | 27.01 | 28.27 | 28.74 | 29.61 | 30.19 | 30.79 | 31.40 |
| Minivan | DSL HEV | M.DHEV | | | 44.22 | 43.95 | 44.50 | 45.13 | 46.03 | 46.96 |
| Minivan | DSL | M.DSL | 34.87 | 36.07 | 36.75 | 36.95 | 37.70 | 38.24 | 39.01 | 39.79 |
| Minivan | Ethanol Flex Fuel | M.ETHX | 25.69 | 27.36 | 28.68 | 29.32 | 30.35 | 31.04 | 31.66 | 32.29 |
| Minivan | Fuel Cell - Gasoline | M.FCG | | | 36.95 | 39.39 | 41.20 | 44.74 | 45.63 | 46.54 |
| Minivan | Fuel Cell - Hydrogen | M.FCH | | | 43.23 | 46.09 | 48.21 | 52.35 | 53.40 | 54.46 |
| Minivan | Conventional | M.GSL | 25.67 | 27.51 | 28.68 | 29.29 | 30.32 | 30.99 | 31.61 | 32.25 |
| Minivan | HEV | M.HEV | | 38.10 | 42.97 | 45.62 | 47.94 | 52.27 | 53.31 | 54.38 |
| Minivan | LPG | M.LPG | 27.11 | 28.93 | 30.14 | 30.71 | 31.72 | 32.44 | 33.09 | 33.75 |
| Minivan | LPG Flex Fuel | M.LPGX | 25.99 | 27.77 | 29.00 | 29.54 | 30.53 | 31.17 | 31.79 | 32.43 |
| Minivan | PHEV | M.PHEV | | | 60.89 | 60.89 | 60.89 | 66.38 | 67.70 | 69.06 |
| Mini Compact | Adv GSL | MC.AGSL | 29.15 | 32.38 | 33.48 | 34.11 | 35.09 | 35.61 | 36.32 | 37.05 |
| Mini Compact | Electric | MC.ELC | 38.10 | 48.14 | 48.45 | 48.79 | 49.50 | 50.09 | 51.09 | 52.12 |
| Mini Compact | Conventional | MC.GSL | 25.35 | 28.16 | 29.11 | 29.66 | 30.51 | 30.97 | 31.59 | 32.22 |
| Mini Compact | HEV | MC.HEV | 35.83 | 36.69 | 40.50 | 43.49 | 45.76 | 49.71 | 50.71 | 51.72 |
| Pickup | Adv GSL | P.AGSL | 23.53 | 25.31 | 26.60 | 27.34 | 28.29 | 28.88 | 29.46 | 30.05 |
| Pickup | CNG | P.CNG | 20.70 | 21.93 | 22.78 | 23.28 | 24.01 | 24.39 | 24.88 | 25.38 |
| Pickup | CNG Flex Fuel | P.CNGX | 18.75 | 20.02 | 20.93 | 21.42 | 22.02 | 22.34 | 22.79 | 23.25 |
| Pickup | DSL | P.DSL | 25.75 | 27.86 | 28.58 | 28.90 | 29.54 | 29.95 | 30.55 | 31.16 |
| Pickup | Ethanol Flex Fuel | P.ETHX | 20.12 | 21.81 | 22.96 | 23.61 | 24.46 | 24.95 | 25.45 | 25.96 |
| Pickup | Conventional | P.GSL | 20.11 | 21.63 | 22.74 | 23.37 | 24.18 | 24.69 | 25.18 | 25.69 |
| Pickup | HEV | P.HEV | | 0.00 | 32.42 | 36.56 | 38.47 | 41.91 | 42.75 | 43.60 |
| Pickup | LPG | P.LPG | 20.03 | 21.37 | 22.41 | 23.01 | 23.83 | 24.32 | 24.80 | 25.30 |
| Pickup | LPG Flex Fuel | P.LPGX | 19.29 | 20.66 | 21.64 | 22.19 | 22.91 | 23.33 | 23.80 | 24.28 |
| Pickup | PHEV | P.PHEV | | | 48.85 | 48.85 | 48.85 | 53.23 | 54.29 | 55.38 |
| SUV-Small | Adv GSL | SS.AGSL | 27.09 | 30.01 | 31.42 | 32.29 | 33.62 | 34.29 | 34.98 | 35.68 |
| SUV-Small | DSL HEV | SS.DHEV | | | | 43.76 | 43.99 | 44.61 | 45.51 | 46.42 |
| SUV-Small | DSL | SS.DSL | 30.97 | 32.52 | 33.66 | 34.02 | 34.85 | 35.39 | 36.10 | 36.82 |
| SUV-Small | Electric | SS.ELC | 29.89 | 38.43 | 38.55 | 38.66 | 39.20 | 39.71 | 40.50 | 41.31 |
| SUV-Small | Ethanol Flex Fuel | SS.ETHX | | 25.05 | 26.54 | 27.39 | 28.55 | 29.13 | 29.71 | 30.31 |
| SUV-Small | Fuel Cell - Gasoline | SS.FCG | | | 39.48 | 42.08 | 44.02 | 47.81 | 48.76 | 49.74 |
| SUV-Small | Fuel Cell - Hydrogen | SS.FCH | 42.96 | 43.25 | 46.20 | 49.24 | 51.51 | 55.94 | 57.06 | 58.20 |
| SUV-Small | Conventional | SS.GSL | 23.16 | 25.65 | 26.86 | 27.60 | 28.73 | 29.31 | 29.89 | 30.49 |
| SUV-Small | HEV | SS.HEV | | 34.38 | 37.32 | 40.14 | 42.54 | 46.40 | 47.32 | 48.27 |
| SUV-Small | PHEV | SS.PHEV | | | 54.03 | 54.03 | 54.03 | 58.92 | 60.10 | 61.30 |

**Table S3.** Car and light-truck degradation factors.

| Vehicle Type | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|
| Car | 0.877 | 0.880 | 0.923 | 0.926 | 0.929 | 0.932 | 0.932 | 0.932 | 0.932 | 0.932 |
| Light Truck | 0.851 | 0.852 | 0.892 | 0.894 | 0.895 | 0.897 | 0.897 | 0.897 | 0.897 | 0.897 |

The $CO_2$ emissions of the vehicles (in $gCO_2$/mile) are based on the carbon content of the fuels (lbs $CO_2$/MMBtu) divided by the efficiency of the vehicles (which are converted to miles per MMBtu) and times a converting factor of 453.59 g/lb. $CO_2$ emission factors for key transportation fuels are listed in Table S4. The emission factor of blended gasoline will depend on the amount of biofuels blended in the gasoline and the $CO_2$ emission factors of biofuels.

**Table S4.** Carbon emission factors of transportation fuels. Source: *(14)*

| Fuel | Emission coefficients (lbs $CO_2$/MMBtu) |
|---|---|
| Reformulated or low-sulfur gasoline | 168.87 |
| Low-sulfur diesel | 173.96 |
| Liquefied petroleum gas (LPG) | 149.74 |
| Methane | 158.83 |
| Compressed natural gas (CNG) | 130.71 |

*Ethanol production costs, efficiency and emissions*

Table S5 describes the production process for ethanol fuel including the characterization of the technologies (capital and operation and maintenance costs, efficiency, emissions), energy sources, feedstocks, and co-products. The technology described below represents a generic dry mill technology and a generic "cellulosic technology" that is based on the production process converting switchgrass to ethanol even though the cellulosic resources included in the database encompass a wider range of potential cellulosic resources including energy crops, agricultural residues, forestry residues, and urban wood/milling waste.

**Table S5.** Input assumptions for corn ethanol and cellulosic ethanol production costs, efficiencies, and emissions.

| Corn (dry mill) | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|
| Investment cost (2000$M/PJ/a) | 16.8 | 15.3 | 15.3 | 15.3 | 15.3 | 15.3 | 15.3 | 15.3 | 15.3 | 15.3 |
| Variable O&M* (2000$M/PJ/a) | -0.199 | -0.199 | -0.199 | -0.199 | -0.199 | -0.199 | -0.199 | -0.199 | -0.199 | -0.199 |
| Emission coefficient** (Mil. Tonnes C/PJ) | -0.0059 | -0.0067 | -0.0069 | -0.0070 | -0.0071 | -0.0072 | -0.0073 | -0.0074 | -0.0075 | -0.0076 |
| Availability factor | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Energy carrier output (PJ): Ethanol | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Energy carrier input (PJ): Corn | 1.74 | 1.70 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 | 1.67 |
| Energy carrier input (PJ): Natural gas | 0.43 | 0.38 | 0.37 | 0.37 | 0.36 | 0.35 | 0.35 | 0.34 | 0.33 | 0.33 |
| Energy carrier input (PJ): electricity | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| Residual capacity (PJ/a) | 348 | 1248 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Cellulosic** | **2005** | **2010** | **2015** | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
| Investment cost (2000$M/PJ/a) | | | 56.2 | 56.2 | 56.2 | 50.6 | 50.6 | 50.6 | 50.6 | 50.6 |
| Variable O&M* (2000$M/PJ/a) | | | 4.7 | 4.7 | 4.7 | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 |
| Emission coefficient** (Mil. Tonnes C/PJ) | | | -0.0146 | -0.0147 | -0.0148 | -0.0149 | -0.0150 | -0.0150 | -0.0151 | -0.0152 |
| Availability factor | | | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 |
| Energy carrier output (PJ): Ethanol | | | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Energy carrier input (PJ):Herbaceous crops | | | 1.83 | 1.83 | 1.83 | 1.74 | 1.74 | 1.74 | 1.74 | 1.74 |
| Energy carrier input (PJ): electricity | | | -0.07 | -0.07 | -0.07 | -0.09 | -0.09 | -0.09 | -0.09 | -0.09 |

* O&M includes labor, chemical inputs, and coproduct credits, and excludes debt service, depreciation, electricity, natural gas, and biomass feedstocks.

** Emission coefficient ignores coproduct credits for exported electricity, assuming these are handled by "negative electricity." The emission factors do not explicitly account for the issue of induced land use conversion and large $CO_2$ emissions by some biofuel feedstock.

Most of the values for corn ethanol are extracted from GREET 1.7. We made many modifications in various places in order to be consistent with MARKAL's general modeling philosophy. These changes are briefly summarized below. The emission factors shown above do not include the full upstream energy or emissions for feedstock production but they include the two largest contributors: nitrogen fertilizer production and soil $N_2O$ emissions from N fertilizer application. They also include emissions from corn and switchgrass soil carbon sequestration. Since MARKAL does not model animal feed markets, we incorporate the economic value and greenhouse gas benefits of coproduced distillers grains into the modeled corn ethanol biorefinery. We calculated corn ethanol costs and O&M costs net of coproduct sales from Shapouri, et al *(15)*.

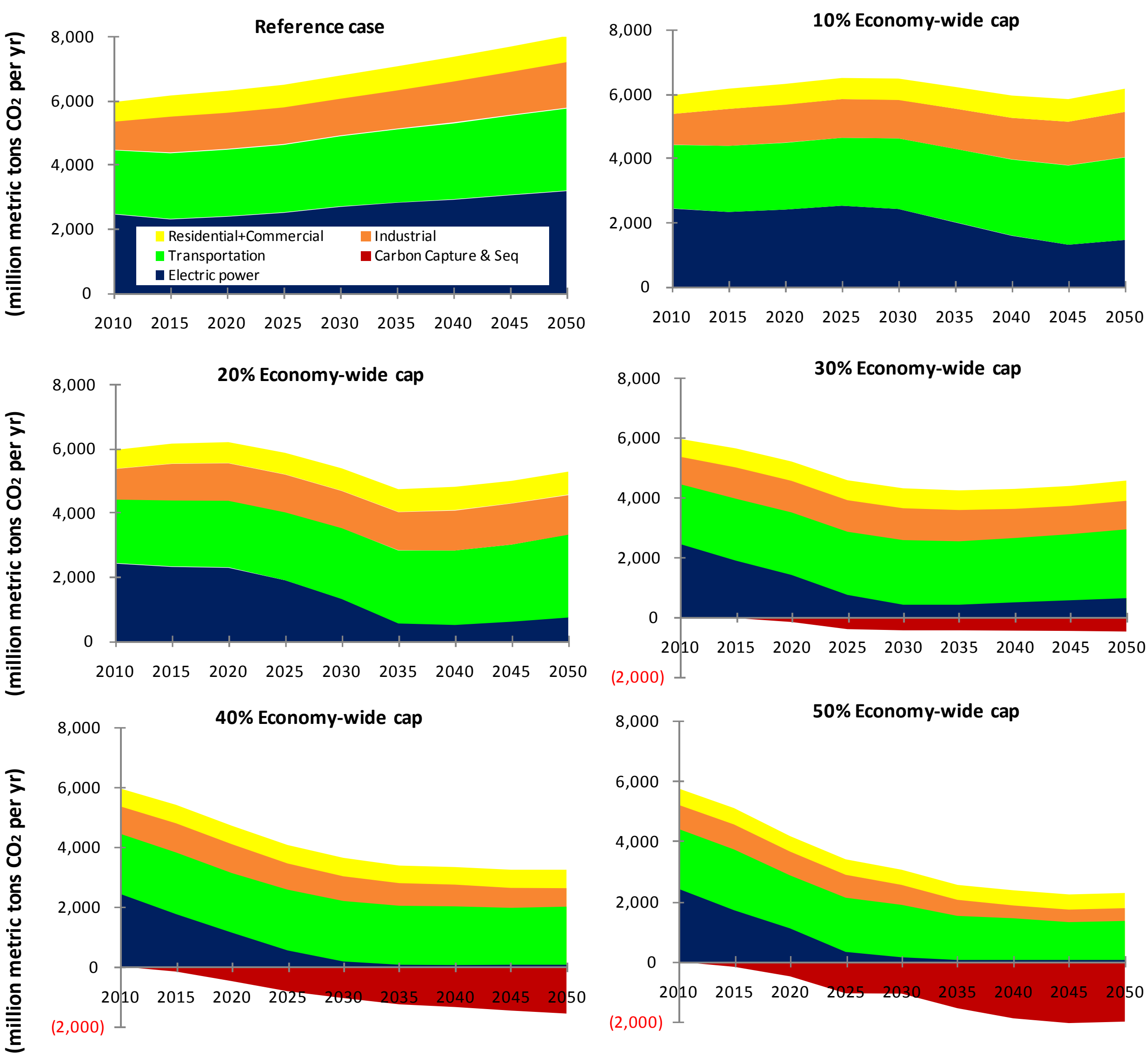
For thermal energy requirement (in natural gas, specifically) for corn production, we assumed a 2% reduction per time-step. Given the variety of ways to reduce energy demand (no-cook fermentation, cogeneration, improved insulation and heat recapture, substitution of biomass and biogas) this seems conservative as an average for the corn ethanol industry. We also assume an increasing conversion rate over time due to better enzymes, fractionation technology, and higher-starch corn varieties.

The technologies to produce cellulosic ethanol are still pre-commercial and are thus much more difficult to project. While there are numerous studies exploring the issue, they vary with regards to the whether they are predicting near-term or long-term technologies. Given our objective of constructing a stylized characterization of ethanol production in MARKAL, we adopt values liberally from several studies *(5-9, 16, 17)* to create an amalgam of shifting technologies, performance, and costs over time to 2050.

## Section S2. Additional Modeling Results

*Projected emissions, emission reductions, and mitigation costs*

Detailed descriptions of the scenarios can be found in Table 1 of the main text. Figure S1 shows projected $CO_2$ emissions between 2010 and 2050 for all the economy-wide cap scenarios (E scenarios) and economy-wide + transportation cap scenarios (E&T scenarios). The projected emission reductions in the transportation sector are comparable between 40%E (40% economy-wide cap) and 10%E&T (10% economy-wide cap + transportation cap). The projected transportation emission reduction for 50%E is between 20%E&T and 30%E&T.



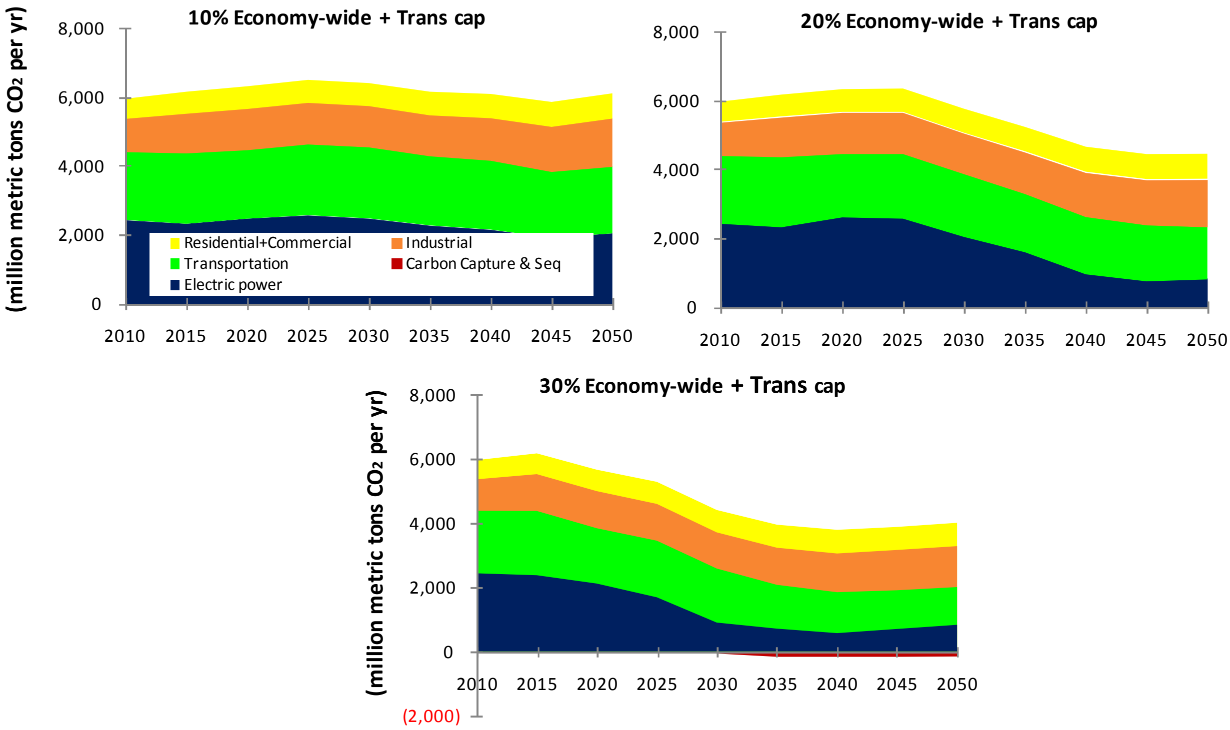



**Figure S1.** Projected $CO_2$ emissions by sector, 2010-2050.

Figure S2 shows the total $CO_2$ emission reductions and Figure S3 shows the marginal costs of emission reduction for the transportation sector. For comparison, the economy-wide marginal costs of $CO_2$ emission reduction for 30%E and 40%E are also shown. The total $CO_2$ emission reduction with no international offsets examined in the EIA's analysis of S. 2191 is 3030 million metric tons $CO_2$-equivalent in 2030 *(18)*. This roughly corresponds to our 30%E scenario (2879 million metric tons $CO_2$ reduction) in 2030. The model estimates that the marginal $CO_2$ mitigation costs for the 30% economy-wide cap scenario (30%E) are \$70, \$126, and \$213 per metric ton $CO_2$ (in 2000 dollars) in 2030, 2040, and 2050 respectively. The interpretation of the marginal abatement costs presented here should be interpreted with great caution. As mentioned in the main text, the goal of this paper is not to analyze the cost impacts of a particular policy, but to inform policy design regarding the potential roles of transportation mitigation strategies and the importance of uncertainties. More importantly, the discussion about $CO_2$ mitigation and its costs should be accompanied by its benefits in avoided damages and increased welfare. Our studies do not attempt to quantify the benefits of $CO_2$ mitigation, which are often argued to be greater than its costs *(19)*.

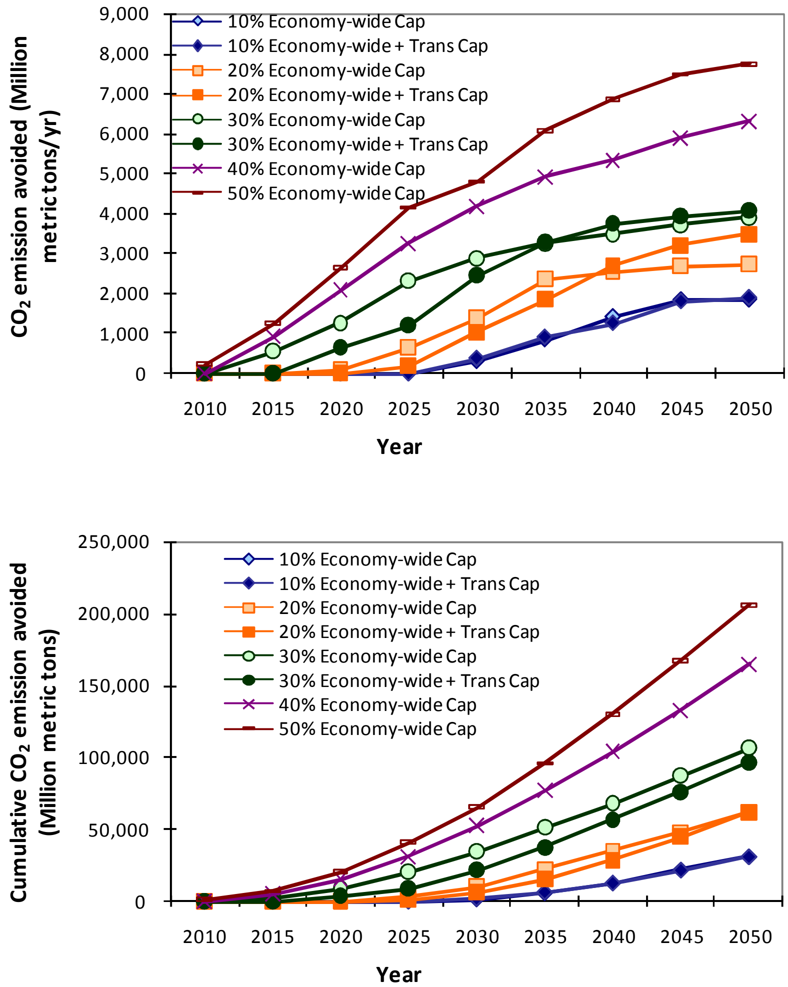



**Figure S2.** $CO_2$ emissions reduction per year (top) and total cumulative $CO_2$ emissions reduction (bottom).

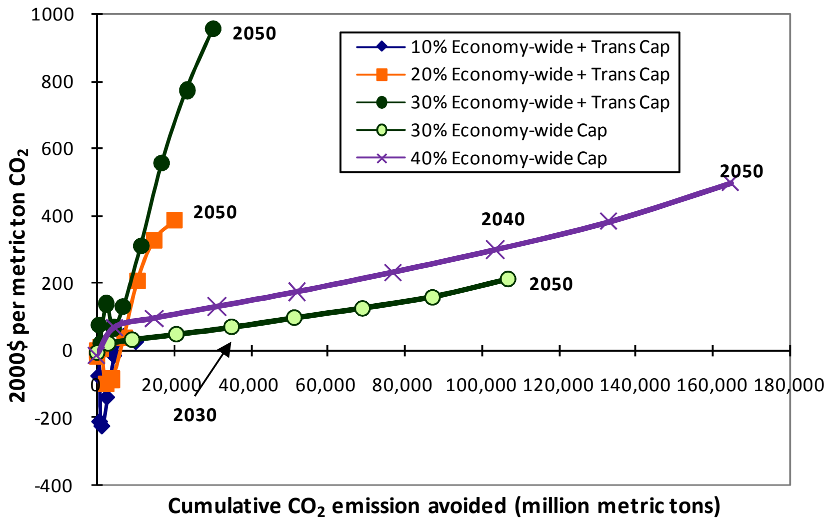



**Figure S3.** Marginal $CO_2$ mitigation costs for the transportation sector (10%-30% Economy-wide + transportation cap) and the economy-wide marginal $CO_2$ mitigation costs (30-40% Economy-wide cap).

*Mitigation contribution from vehicle travel demand reduction, vehicle efficiency improvement, and fuel $CO_2$ intensity reduction*

To isolate the amount of $CO_2$ emission reduction by a specific mitigation strategy within a dynamic model can be tricky because so many variables are changing at one time. We therefore devised a simple estimation that approximates the contribution of $CO_2$ emission mitigations from vehicle travel demand reduction, vehicle efficiency improvement, and fuel $CO_2$ intensity reduction. The calculation is shown in Table S6.

**Table S6.** Modelling results and methods to estimate $CO_2$ emission mitigations from vehicle travel demand reduction, vehicle efficiency improvement, and reduction in fuel $CO_2$ intensity.

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| **Emissions from light-duty vehicles (million metric tons CO2)** Emission factors are based on fuel carbon content and not on a life cycle-based (with the exception of ethanol, per explanation in Section S1). Emissions from electricity use are accounted in the electric sector. | | | | | | | | | |
| Reference Case | 1,078 | 1,072 | 1,062 | 1,105 | 1,198 | 1,229 | 1,237 | 1,296 | 1,392 |
| 10%E&T | 1,075 | 1,087 | 908 | 932 | 953 | 888 | 855 | 763 | 758 |
| 20%E&T | 1,071 | 1,068 | 834 | 843 | 810 | 659 | 617 | 557 | 400 |
| 30&E&T | 1,066 | 1,042 | 775 | 772 | 714 | 384 | 279 | 175 | 118 |
| 50%E | 1,071 | 1,066 | 823 | 828 | 795 | 505 | 423 | 255 | 247 |
| **Travel demand (billion VMT)** | | | | | | | | | |
| Reference Case | 2,799 | 3,125 | 3,474 | 3,839 | 4,227 | 4,565 | 4,930 | 5,324 | 5,750 |
| 10%E&T | 2,799 | 3,125 | 3,422 | 3,839 | 4,227 | 4,565 | 4,930 | 5,324 | 5,750 |
| 20%E&T | 2,799 | 3,125 | 3,422 | 3,839 | 4,227 | 4,565 | 4,930 | 5,324 | 5,750 |
| 30&E&T | 2,799 | 3,125 | 3,370 | 3,839 | 4,227 | 4,565 | 4,930 | 5,324 | 5,750 |
| 50%E | 2,799 | 3,125 | 3,370 | 3,839 | 4,227 | 4,565 | 4,930 | 5,324 | 5,750 |
| **Fuel use (trillion Btu)** | | | | | | | | | |
| Reference Case | 14,748 | 14,906 | 15,187 | 16,158 | 17,553 | 18,153 | 18,989 | 20,031 | 20,769 |
| 10%E&T | 14,712 | 15,101 | 13,094 | 13,741 | 14,156 | 13,549 | 14,018 | 14,374 | 14,376 |
| 20%E&T | 14,669 | 14,845 | 12,204 | 12,715 | 12,531 | 11,461 | 11,718 | 12,379 | 12,638 |
| 30&E&T | 14,600 | 14,504 | 11,528 | 11,986 | 11,712 | 9,435 | 9,404 | 10,083 | 10,796 |
| 50%E | 14,665 | 14,815 | 11,993 | 12,477 | 12,253 | 10,274 | 10,257 | 10,479 | 11,194 |
| **Fleet average efficiency (mpg)** | | | | | | | | | |
| Reference Case | 23.5 | 24.8 | 26.7 | 28.1 | 29.4 | 31.2 | 32.2 | 33 | 34.3 |
| 10%E&T | 23.6 | 25.7 | 32.4 | 34.7 | 37 | 41.8 | 43.6 | 45.9 | 49.6 |
| 20%E&T | 23.7 | 26.1 | 34.8 | 37.5 | 41.8 | 49.4 | 52.2 | 53.4 | 56.4 |
| 30&E&T | 23.8 | 26.7 | 36.3 | 39.7 | 44.8 | 60 | 65 | 65.5 | 66.1 |
| 50%E | 23.7 | 26.2 | 34.9 | 38.2 | 42.8 | 55.1 | 59.6 | 63 | 63.7 |

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| **Method to estimate the contributions of $CO_2$ emission mitigations (million metric tons $CO_2$) from VMT reduction, efficiency improvement and fuel $CO_2$ intensity reduction.** Shaded areas are hypothetical emission changes *if* all other factors are held constant except the specified variable(s) | | | | | | | | | |
| *Reference Case* | | | | | | | | | |
| Hold emission constant | 1,078 | 1,078 | 1,078 | 1,078 | 1,078 | 1,078 | 1,078 | 1,078 | 1,078 |
| Emission changes: VMT only | 1,078 | 1,204 | 1,338 | 1,479 | 1,628 | 1,758 | 1,899 | 2,051 | 2,215 |
| Emission changes: VMT & efficiency | 1,078 | 1,141 | 1,181 | 1,237 | 1,302 | 1,327 | 1,388 | 1,464 | 1,518 |
| Actual total emission changes | 1,078 | 1,072 | 1,062 | 1,105 | 1,198 | 1,229 | 1,237 | 1,296 | 1,392 |
| *10% Economy-wide + Trans Cap (10%E&T)* | | | | | | | | | |
| Emission changes: VMT only | 1,078 | 1,204 | 1,318 | 1,479 | 1,628 | 1,758 | 1,899 | 2,051 | 2,215 |
| Emission changes: VMT & efficiency | 1,078 | 1,106 | 959 | 1,007 | 1,037 | 993 | 1,027 | 1,053 | 1,053 |
| Emission mitigation: VMT | 0 | 0 | 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| Emission mitigation: efficiency | 0 | 34 | 201 | 230 | 265 | 334 | 361 | 411 | 465 |
| Emission mitigation: fuel $CO_2$ intensity | 3 | -50 | -67 | -57 | -20 | 6 | 22 | 122 | 169 |
| *20% Economy-wide + Trans Cap (20%E&T)* | | | | | | | | | |
| Emission changes: VMT only | 1,078 | 1,204 | 1,318 | 1,479 | 1,628 | 1,758 | 1,899 | 2,051 | 2,215 |
| Emission changes: VMT & efficiency | 1,078 | 1,091 | 897 | 934 | 921 | 842 | 861 | 910 | 929 |
| Emission mitigation: VMT | 0 | 0 | 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| Emission mitigation: efficiency | 0 | 50 | 264 | 302 | 382 | 485 | 527 | 554 | 589 |
| Emission mitigation: fuel $CO_2$ intensity | 6 | -46 | -56 | -40 | 6 | 85 | 94 | 184 | 403 |
| *30% Economy-wide + Trans Cap (30%E&T)* | | | | | | | | | |
| Emission changes: VMT only | 1,078 | 1,204 | 1,298 | 1,479 | 1,628 | 1,758 | 1,899 | 2,051 | 2,215 |
| Emission changes: VMT & efficiency | 1,078 | 1,071 | 851 | 885 | 865 | 696 | 694 | 744 | 797 |
| Emission mitigation: VMT | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 | 0 |
| Emission mitigation: efficiency | 0 | 70 | 290 | 352 | 438 | 630 | 694 | 720 | 721 |
| Emission mitigation: fuel $CO_2$ intensity | 12 | -40 | -43 | -18 | 46 | 215 | 264 | 401 | 553 |
| *50% Economy-wide Cap (50%E)* | | | | | | | | | |
| Emission changes: VMT only | 1,078 | 1,204 | 1,298 | 1,479 | 1,628 | 1,758 | 1,899 | 2,051 | 2,215 |
| Emission changes: VMT & efficiency | 1,078 | 1,089 | 881 | 917 | 901 | 755 | 754 | 770 | 823 |
| Emission mitigation: VMT | 0 | 0 | 40 | 0 | 0 | 0 | 0 | 0 | 0 |
| Emission mitigation: efficiency | 0 | 52 | 259 | 319 | 402 | 572 | 634 | 694 | 695 |
| Emission mitigation: fuel $CO_2$ intensity | 7 | -45 | -61 | -42 | 1 | 152 | 181 | 347 | 450 |
| **Method to estimate emission mitigation (million metric tons $CO_2$/yr) from fuel $CO_2$ intensity reduction from ethanol fuels and others** | | | | | | | | | |
| *Total ethanol fuels emissions* | | | | | | | | | |
| Reference case | -31 | -58 | -91 | -126 | -140 | -156 | -188 | -195 | -177 |
| 10% Economy-wide + Trans Cap | -31 | -58 | -86 | -115 | -124 | -142 | -178 | -257 | -272 |
| 20% Economy-wide + Trans Cap | -31 | -58 | -91 | -120 | -126 | -151 | -186 | -262 | -408 |
| 30% Economy-wide + Trans Cap | -31 | -58 | -91 | -126 | -144 | -161 | -212 | -330 | -456 |
| 50% Economy-wide Cap (50%E) | -31 | -58 | -86 | -112 | -108 | -128 | -155 | -266 | -345 |
| *Emission mitigation from fuel $CO_2$ intensity reduction - ethanol fuels* | | | | | | | | | |
| 10% Economy-wide + Trans Cap | 0 | 0 | -5 | -12 | -15 | -14 | -10 | 62 | 95 |
| 20% Economy-wide + Trans Cap | 0 | 0 | 0 | -6 | -14 | -5 | -2 | 66 | 231 |
| 30% Economy-wide + Trans Cap | 0 | 0 | 0 | 0 | 4 | 5 | 24 | 134 | 279 |
| 50% Economy-wide Cap (50%E) | 0 | 0 | -5 | -14 | -32 | -28 | -33 | 71 | 168 |
| *Emission mitigation from fuel $CO_2$ intensity reduction – others* | | | | | | | | | |
| 10% Economy-wide + Trans Cap | 3 | -50 | -61 | -45 | -4 | 20 | 31 | 60 | 74 |
| 20% Economy-wide + Trans Cap | 6 | -46 | -56 | -34 | 20 | 90 | 96 | 118 | 171 |
| 30% Economy-wide + Trans Cap | 12 | -40 | -43 | -17 | 42 | 209 | 241 | 267 | 274 |
| 50% Economy-wide Cap (50%E) | 7 | -45 | -55 | -27 | 33 | 180 | 214 | 276 | 282 |

The average fuel $CO_2$ intensity ($gCO_2/MJ$) for passenger vehicles can be calculated by dividing the total passenger vehicle emissions (million metric tons $CO_2$) by the total fuel use (billion Btu) and then multiplying by a conversion factor of 947.817 Btu/MJ (Figure S4). With the exception of ethanol, fuel $CO_2$ intensity is calculated based on the carbon content of the fuels, shown in Table S4, and not on a life-cycle basis. For ethanol feedstocks, the considerable $N_2O$ emissions are included as $CO_2$ equivalents because they can comprise a sizeable share of the direct GHG effects of bioenergy crop production. The emission factors for corn ethanol and cellulosic ethanol are listed in Table S5. Note that our paper only considers two generic types of ethanol: corn ethanol and cellulosic ethanol. Many biofuel production pathways can contribute to significantly lower greenhouse gas emission reductions *(20, 21)*, and this would be an important research area that needs to be incorporated into our future database. The emission accounting in our database adopts the sector-specific approach. Therefore emissions from electricity use for plug-in hybrid vehicles will be accounted for in the electric sector.

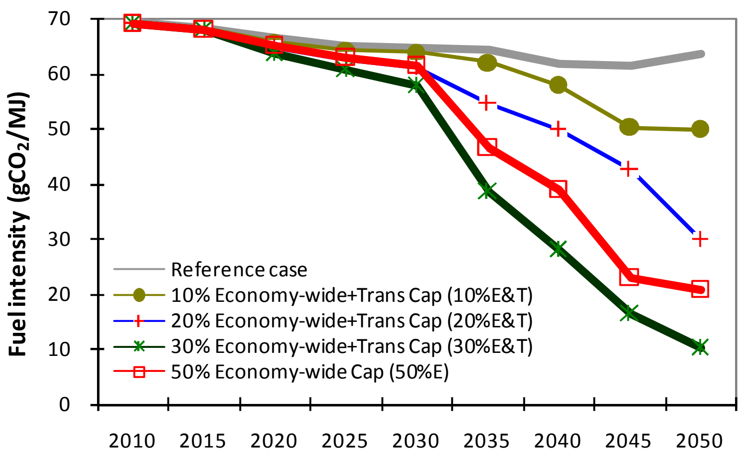



**Figure S4.** The average fuel $CO_2$ intensity for passenger vehicles by scenario. The emissions for the $CO_2$ intensity of the fuels are sector-specific and not life-cycle based.

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