# Cities & transportation systems – what can cities do?
# MIT 11.165/477, 11.286J

David Hsu
Associate Professor
Urban Studies & Planning
MIT DUSP

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# Materials for today

- Robert Bullard. Addressing Urban Transportation Equity in the United States. Fordham Urban Law Journal, 31(5):1183, January 2003. URL.
- Tim Gore. Confronting carbon inequality: putting climate justice at the heart of the COVID-19 recovery, September 2020. URL.
- Colin McKerracher, Aleksandra O'Donovan, Nikolas Soulopoulos, Andrew Grant, Siyi Mi, David Doherty, Ryan Fisher, Corey Cantor, Jinghong Lyu, Kwasi Ampofo, Andy Leach, Yayoi Sekine, Laura Malo Yague, William Edmonds, Komal Kareer, and Takehiro Kawahara. Electric Vehicle Outlook 2022. Technical report, Bloomberg New Energy Finance, 2022. URL.
- THIS LECTURE: Cambridge Systematics. "Moving Cooler: An Analysis of Transportation Strategies for Reducing Greenhouse Gas Emissions." Urban Land Institute. 2009. URL.

# What can cities do?

Let me remind you that we are focusing on cities because of:

- population
- economic activity
- consumption $>$ production (physical)

Raises questions about how we make the necessary changes in cities:

- land use and the built environment
- areas connected to cities (all of them)
- long-lived, durable, seemingly slow to change
- can we do it fast / broadly enough? WHO? HOW?
- what should we do first?

# Infrastructure characteristics

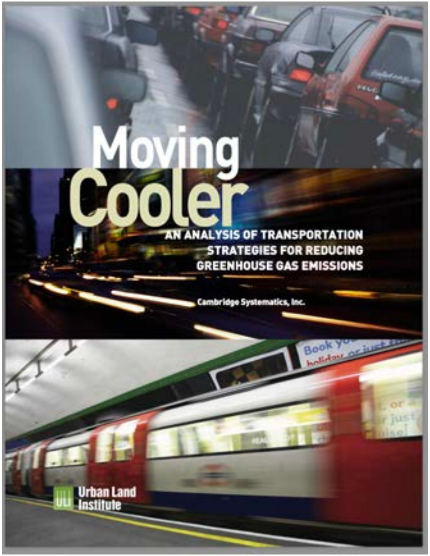
BIG:

- long-lived, durable, seemingly slow to change
- expensive: assets, investment, usually debt-financed
- large volumes, continuous operations, global systems (supply chains!)
- large footprints, areas, impact
- EJ concerns: often cited near poor & minority communities. Why? (Bullard 2003 article)

# Energy density

| Concern | Metric | Critical application |
|---|---|---|
| Weight | kWh / kg (energy storage) | Planes, cars, e-bikes |
| | kWh / ton (shipping weight) | Ships, trucks, trains |
| Volume | kWh / liter (fuel tank) | Planes, cars, trucks |
| | kWh / liter (freight volume) | Ships, trucks, trains |
| Land area | kWh / acre (biomass) | To produce liquid fuels, H2 |
| | kWh / acre (solar, wind) | To produce electricity |
| Cost | kWh / $ | For pretty much everything |

# Moving Cooler strategies, 2009




## Study Author

**Cambridge Systematics, Inc.**

Cambridge Systematics, Inc., specializes in transportation, dedicated to ensuring that transportation investments deliver the best possible results. It is recognized as a leader in the development and implementation of innovative policy and planning solutions, objective analysis, and technology applications. Cambridge Systematics works to build the capacity of the transportation community to understand and address both sides of the climate change challenge: to develop strategies to reduce greenhouse gas emissions from transportation, and to prepare for the potential effects of climate change on transportation systems.

## *Moving Cooler* Steering Committee

**American Public Transportation Association**
Rob Padgette

**Environmental Defense Fund**
Michael Replogle

**Federal Highway Administration**
April Marchese and John Davies

**Federal Transit Administration**
Tina Hodges

**Intelligent Transportation Society of America**
Leslie Bellas

**Natural Resources Defense Council**
Deron Lovaas and Nathan Sandwick

**Shell Oil Company**
Miriam Conner

**Urban Land Institute**
Robert Dunphy, Rachelle Levitt, and Dean Schwanke

**U.S. Environmental Protection Agency**
Ken Adler

## Project Facilitation

**Collaborative Strategies Group, LLC**

Collaborative Strategies Group, LLC, is a consulting firm specializing in facilitation, public outreach and communication, project management, and public policy development for governments, businesses, communities, and organizations that need help navigating complex problem-solving, decision-making, and relationship-building issues.

# Moving Cooler strategies, 2009

Has:

- telework & less days (Zoom!)
- vehicle technology
- fuel technology
- travel activity
- vehicle system operations
- all modes: passenger, transit, freight, shipping, aviation

Does not have:

- shared vehicles (Zipcar 2000)
- ride-sharing (Uber 2009, Lyft 2012)
- autonomous vehicles (AVs)
- EVs costs greatly decrease
- bike sharing (Amsterdam 1965, Portland 1995, dockless 1998)

# Moving Cooler effects, "performance outcomes"

Yes:

- GHG reduction
- implementation costs
- change in vehicle costs
- equity effects

No:

- (-) travel times?
- (+) expanded options, reduced congestion, greater accessibility
- (+) improved safety
- (+) improvements in livability, improved equity, improved local environmental quality, enhanced public health

# Moving Cooler strategies

- pricing and taxes
- land use and smart growth
- non-motorized transport
- public transportation improvements
- ride-sharing, car-sharing, other commuting strategies
- regulatory strategies
- operational and intelligent transportation (ITS) strategies
- capacity expansion and bottleneck relief
- multimodal freight sector strategies

# Moving Cooler deployment levels and bundles

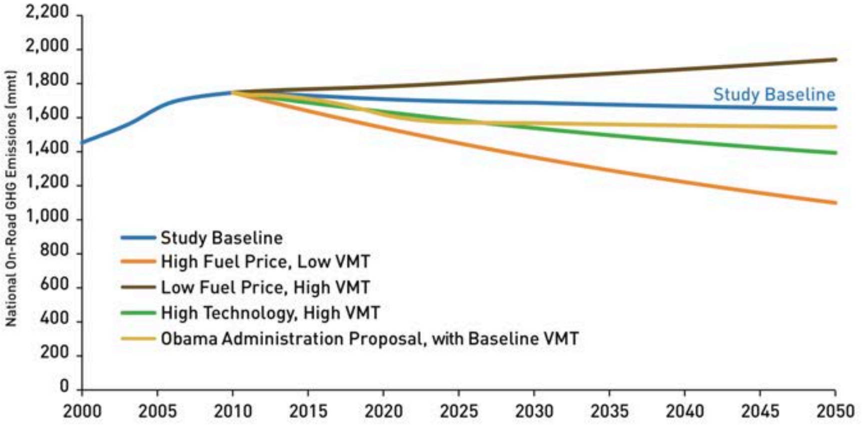
Deployment levels:

- expanded current practice: focused mostly on major metro areas
- aggressive: sooner and more broadly geographically deployed
- maximum effort: maximum national, regional, and local focus

Strategy bundles:

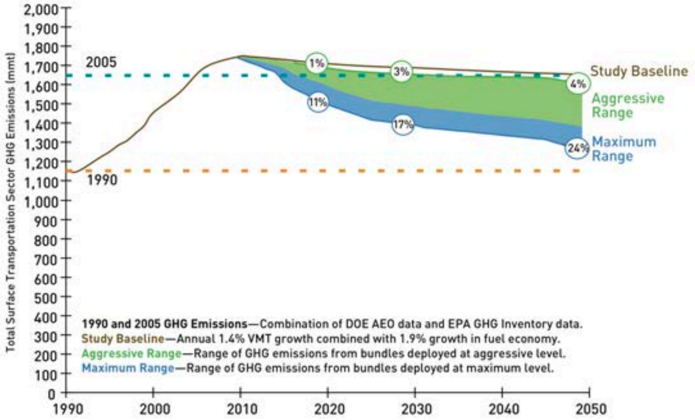
1. near-term / early results
2. long-term / maximum results
3. land-use / transit / non-motorized bundle
4. system / driver efficiency bundle
5. facility bundle
6. low cost bundle

Figure ES.2 ***Moving Cooler* National GHG Emissions Baseline and Baseline Sensitivity**




Note: This figure displays National On-Road GHG emissions as estimated in the *Moving Cooler* baseline, compared with the study's three sensitivity analysis baselines and with the GHG emission estimates, based on President Obama's May 19, 2009, national fuel efficiency standard proposal of 35.5 mpg in 2016.

Figure ES.3 **Range of Annual GHG Emission Reductions of Six Strategy Bundles at Aggressive and Maximum Deployment Levels**
2010 to 2050




Note: This figure displays the GHG emission range across the six bundles for the aggressive and maximum deployment scenarios. The percent reductions are on an annual basis from the study baseline. The 1990 and 2005 baselines are included for reference.

Maximum deployment: 110-470 M barrels per year / 5.7 M/day = 19-82 days per year.

Table 4.15 **Summary of *Moving Cooler* Bundle Analysis Results: Cumulative GHG Reductions, Implementation Costs, and Change in Vehicle Costs by Strategy (at Aggressive and Maximum Deployment Levels)**
2010 to 2050

| | Aggressive Deployment | | | | | Maximum Deployment | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Included Costs | | | | | Included Costs | | | |
| | GHG Reduction (Gt) | Implementation Costs[a] | Change in Vehicle Costs[b] | Imp. Costs Less Vehicle Costs | Net Cost per Tonne[c] | GHG Reduction (Gt) | Implementation Costs[a] | Change in Vehicle Costs[b] | Imp. Costs Less Vehicle Costs | Net Cost per Tonne[c] |
| 1. Near-Term/Early Results | 7.1 | $676 | -$3,211 | -$2,535 | -$356 | 9.3 | $945 | -$4,779 | -$3,834 | -$410 |
| 2. Long-Term/ Maximum Results | 7.6 | $2,611 | -$4,846 | -$2,235 | -$293 | 10.8 | $5,105 | -$7,668 | -$2,563 | -$237 |
| 3. Land Use/Transit/ Nonmotorized Transportation | 3.8 | $1,439 | -$3,270 | -$1,831 | -$484 | 6.3 | $2,390 | -$5,740 | -$3,350 | -$531 |
| 4. System and Driver Efficiency | 5.0 | $1,870 | -$2,214 | -$344 | -$69 | 6.0 | $3,338 | -$2,737 | -$601 | $100 |
| 5. Facility Pricing | 1.4 | $2,371 | -$1,121 | $1,250 | $891 | 1.7 | $4,484 | -$1,656 | $2,828 | $1,632 |
| 6. Low Cost | 7.5 | $599 | -$3,499 | -$2,900 | -$387 | 9.8 | $634 | -$5,103 | -$4,469 | -$457 |

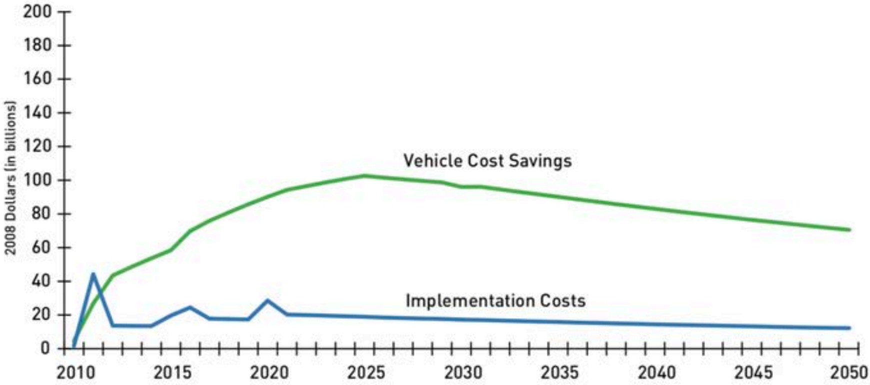
Note: Gt (gigatonne) = one billion metric tonnes.

[a] Implementation cost is the estimated cumulative cost to implement each bundle, including capital, maintenance, operations, and administrative costs.

[b] Vehicle cost is the estimated cumulative reduction in the cost of owning and operating vehicles from a societal perspective, which would result with reductions in VMT and fuel consumption experienced with implementation of each bundle. Vehicle costs **DO NOT** include other costs and benefits that could be experienced as a consequence of implementing each bundle, such as changes in travel time, safety, user fees, environmental quality, and public health.

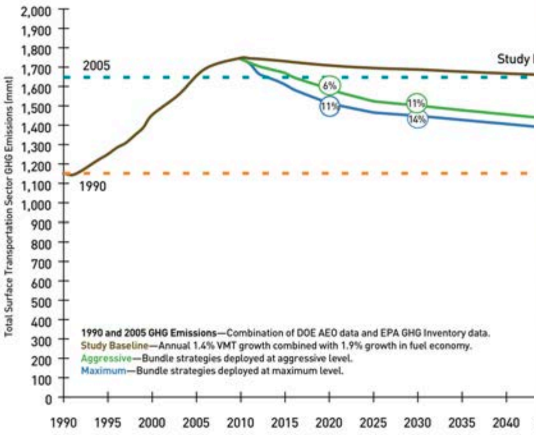
[c] Included cost per tonne is simply the estimated cumulative cost of implementation, less the estimated vehicle cost savings divided by the estimated cumulative reduction in GHG emissions for each bundle.

Figure 4.2 **Implementation Costs and Vehicle Cost Savings for Near-Term/Early Results Bundle at Aggressive Deployment**




Note: This figure displays estimated annual implementation costs (capital, maintenance, operations, and administrative) and annual vehicle cost savings (reduction in the cost of owning and operating a vehicle from reduced VMT and delay). Vehicle cost savings **DO NOT** include other costs and benefits that could be experienced as a consequence of implementing each bundle, such as changes in travel time, safety, user fees, environmental quality, and public health.

Figure 4.1 **GHG Reduction for Near-Term/Early Results Bundle**
2010 to 2050

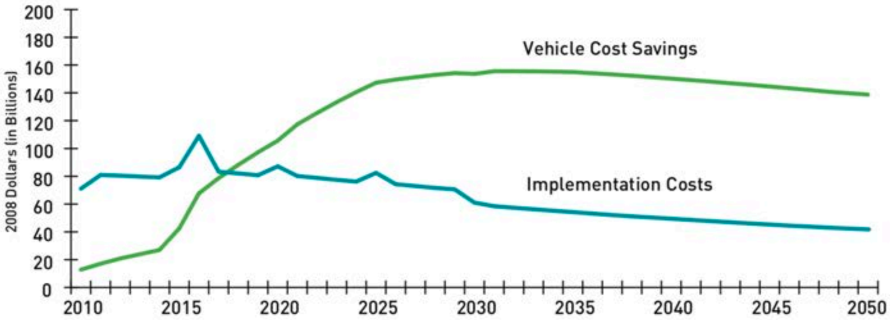



Note: This figure displays the GHG Reduction for Near-Term/Early Reductions Bundle at Aggressive an
Deployment for the 2010 to 2050 time period without economy-wide pricing. Percent reductions are on
from the study baseline.

Table 4.3 **Bundle 1: Near-Term/Early Results**

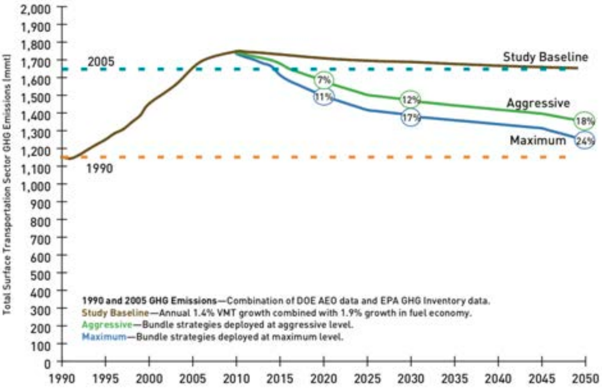
| **GHG Reduction Strategies** |
|---|
| **Pricing Strategies** |
| CBD/Activity Center On-street Parking Pricing |
| New Tax/Higher Tax on Free Private Parking |
| Residential Parking Permits |
| Congestion Pricing |
| **Public Transportation Strategies** |
| Transit Fare Measures |
| Increased Transit Frequency and LOS |
| **HOV/Carpool/Vanpool/Commute Strategies** |
| Car-Sharing |
| Employer-Based Commute Measures |
| **Regulatory Strategies** |
| Urban Parking Restrictions |
| Speed Limit Reductions |
| **Systems Operations and Management Strategies** |
| Eco-Driving |
| Incident Management |
| Road Weather Management |
| Signal Control Management |
| Traveler Information |
| **Multimodal Freight Strategies** |
| Shipping Container Permits |
| LCV Permits |
| Truck Stop Electrification |

Figure 4.4 **Implementation Costs and Vehicle Cost Savings for Long-Term/Maximum Results Bundle at Aggressive Deployment**




Note: This figure displays estimated annual implementation costs (capital, maintenance, operations, and administrative) and annual vehicle cost savings (reduction in the costs of owning and operating a vehicle from reduced VMT and delay). Vehicle cost savings **DO NOT** include other costs and benefits that could be experienced as a consequence of implementing each bundle, such as changes in travel time, safety, user fees, environmental quality, and public health.

Figure 4.3 **GHG Reduction for Long-Term/Maximum Results Bundle**
2010 to 2050



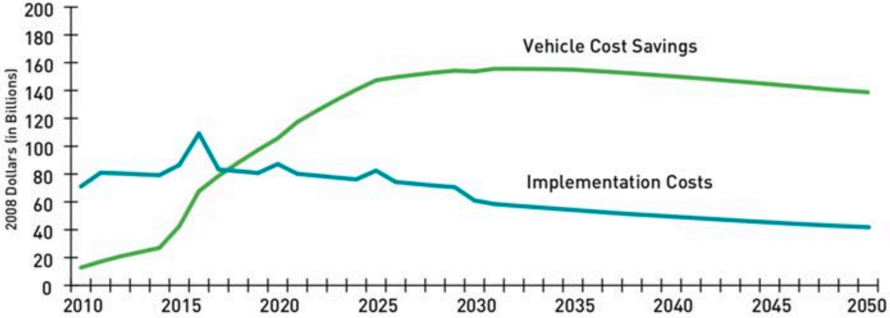

Note: This figure displays the GHG Reduction for Long-Term/Maximum Results Bundle at Aggressive and Maximum Deployment for the 2010 to 2050 time period without economy-wide pricing. Percent reductions are on an annual basis from the study baseline.



Table 4.5 **Bundle 2: Long-Term/Maximum Results**

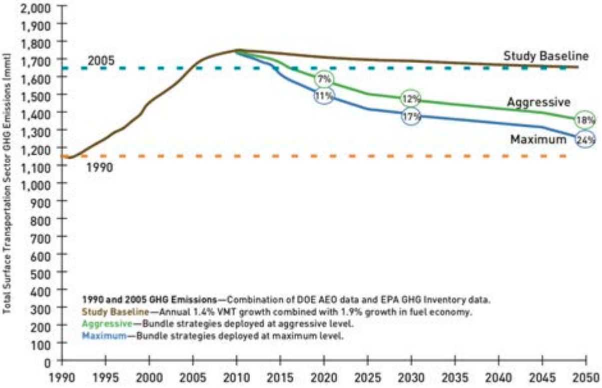
| GHG Reduction Strategies |
|---|
| **Pricing Strategies** |
| CBD/Activity Center On-street Parking Pricing |
| New Tax/Higher Tax on Free Private Parking |
| Residential Parking Permits |
| Congestion Pricing |
| Intercity Tolls |
| **Land Use and Smart Growth Strategies/Nonmotorized Strategies** |
| Combined Land Use |
| Combined Pedestrian |
| Combined Bicycling |
| **Public Transportation Strategies** |
| Transit Fare Measures |
| Increased Frequency, LOS, and Extent |
| Urban Transit Expansion |
| Intercity Passenger Rail Expansion |
| High-Speed Passenger Rail |
| **HOV/Carpool/Vanpool/Commuting Strategies** |
| HOV Lanes |
| HOV Lanes (24-hour applicability) |
| Car-Sharing |
| Employer-Based Commute Measures |
| **Regulatory Strategies** |
| Urban Nonmotorized Zones |
| Urban Parking Restrictions |
| Speed Limit Reductions |
| **Systems Operations and Management Strategies** |
| Eco-driving |
| Freeway Management: Ramp Metering, VMS, Active Traffic Management, and Integrated Corridor Management |
| Incident Management |
| Road Weather Management |
| Signal Management |
| Traveler Information |
| Vehicle Infrastructure Integration (VII) |
| Bottleneck Relief |
| Highway Capacity Expansion |
| **Multimodal Freight Strategies** |
| Rail Capacity Improvements |
| Marine System Improvements |
| Shipping Container Permits |
| LCV Permits |
| WIM Screening |
| Weigh Station Bypass |
| Truck Stop Electrification |
| Truck-Only Toll Lanes |
| Urban Consolidation Centers |

Figure 4.4 **Implementation Costs and Vehicle Cost Savings for Long-Term/Maximum Results Bundle at Aggressive Deployment**




Note: This figure displays estimated annual implementation costs (capital, maintenance, operations, and administrative) and annual vehicle cost savings (reduction in the costs of owning and operating a vehicle from reduced VMT and delay). Vehicle cost savings **DO NOT** include other costs and benefits that could be experienced as a consequence of implementing each bundle, such as changes in travel time, safety, user fees, environmental quality, and public health.

Figure 4.3 **GHG Reduction for Long-Term/Maximum Results Bundle**
2010 to 2050




Note: This figure displays the GHG Reduction for Long-Term/Maximum Results Bundle at Aggressive and Maximum Deployment for the 2010 to 2050 time period without economy-wide pricing. Percent reductions are on an annual basis from the study baseline.

Table 4.5 **Bundle 2: Long-Term/Maximum Results**

| GHG Reduction Strategies |
|---|
| **Pricing Strategies** |
| CBD/Activity Center On-street Parking Pricing |
| New Tax/Higher Tax on Free Private Parking |
| Residential Parking Permits |
| Congestion Pricing |
| Intercity Tolls |
| **Land Use and Smart Growth Strategies/Nonmotorized Strategies** |
| Combined Land Use |
| Combined Pedestrian |
| Combined Bicycling |
| **Public Transportation Strategies** |
| Transit Fare Measures |
| Increased Frequency, LOS, and Extent |
| Urban Transit Expansion |
| Intercity Passenger Rail Expansion |
| High-Speed Passenger Rail |
| **HOV/Carpool/Vanpool/Commuting Strategies** |
| HOV Lanes |
| HOV Lanes (24-hour applicability) |
| Car-Sharing |
| Employer-Based Commute Measures |
| **Regulatory Strategies** |
| Urban Nonmotorized Zones |
| Urban Parking Restrictions |
| Speed Limit Reductions |
| **Systems Operations and Management Strategies** |
| Eco-driving |
| Freeway Management: Ramp Metering, VMS, Active Traffic Management, and Integrated Corridor Management |
| Incident Management |
| Road Weather Management |
| Signal Management |
| Traveler Information |
| Vehicle Infrastructure Integration (VII) |
| Bottleneck Relief |
| Highway Capacity Expansion |
| **Multimodal Freight Strategies** |
| Rail Capacity Improvements |
| Marine System Improvements |
| Shipping Container Permits |
| LCV Permits |
| WIM Screening |
| Weigh Station Bypass |
| Truck Stop Electrification |
| Truck-Only Toll Lanes |
| Urban Consolidation Centers |

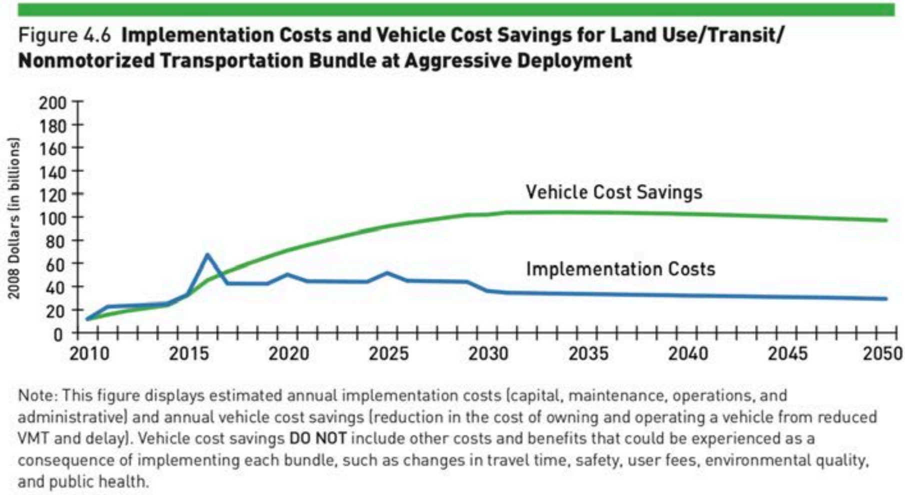
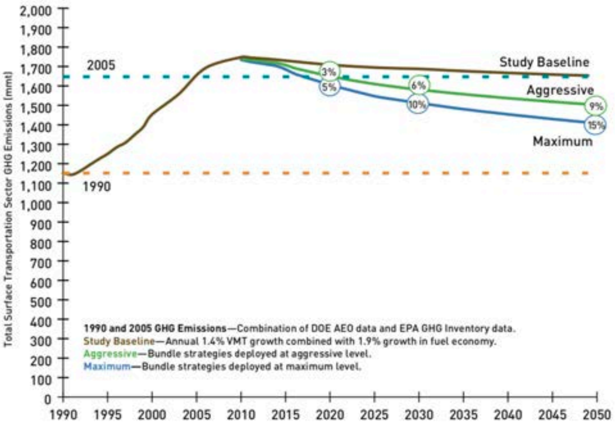


Figure 4.6 Implementation Costs and Vehicle Cost Savings for Land Use/Transit/ Nonmotorized Transportation Bundle at Aggressive Deployment
2008 Dollars (in billions)
200
180
160
140
120
100
80
60
40
20
0
2010
2015
2020
2025
2030
2035
2040
2045
2050
Vehicle Cost Savings
Implementation Costs
Note: This figure displays estimated annual implementation costs (capital, maintenance, operations, and administrative) and annual vehicle cost savings (reduction in the cost of owning and operating a vehicle from reduced VMT and delay). Vehicle cost savings DO NOT include other costs and benefits that could be experienced as a consequence of implementing each bundle, such as changes in travel time, safety, user fees, environmental quality, and public health.

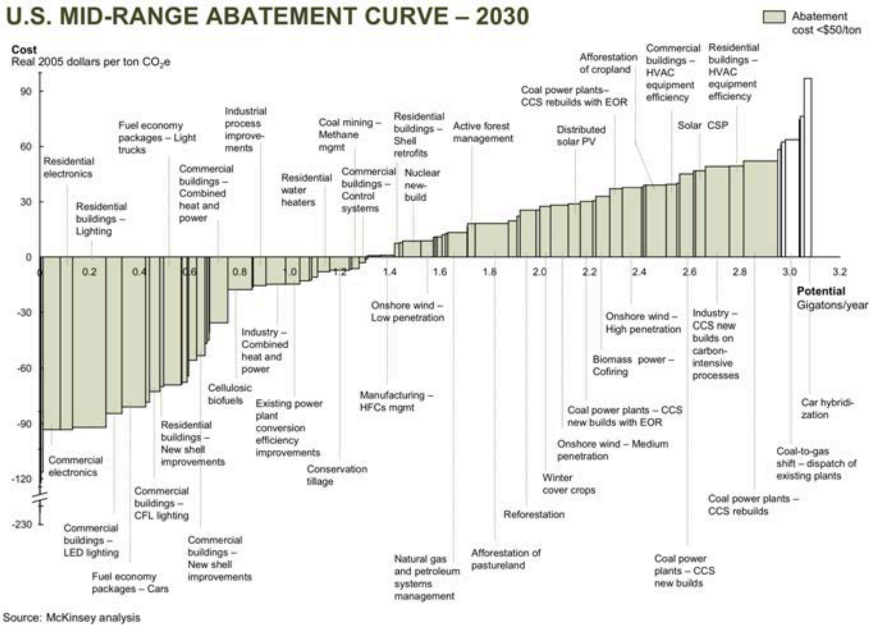
Figure 4.5 **GHG Reduction for Land Use/Transit/Nonmotorized Transportation Bundle** 2010 to 2050




Note: This figure displays the GHG Reduction for Land Use/Transit/Nonmotorized Transportation Bundle at Aggressive and Maximum Deployment for the 2010 to 2050 time period without economy-wide pricing. Percent reductions are on an annual basis from the study baseline.

Table 4.7 **Bundle 3: Land Use/Transit/ Nonmotorized Transportation**

| GHG Reduction Strategies |
|---|
| **Pricing Strategies** |
| CBD/Activity Center On-Street Parking Pricing |
| New Tax/Higher Tax on Free Private Parking |
| Residential Parking Permits |
| Congestion Pricing |
| **Land Use and Smart Growth Strategies/Nonmotorized Strategies** |
| Combined Land Use |
| Combined Pedestrian |
| Combined Bicycling |
| **Public Transportation Strategies** |
| Transit Fare Measures |
| Increased Frequency, LOS, and Extent |
| Urban Transit Expansion |
| Intercity Passenger Rail Expansion |
| High-Speed Passenger Rail |
| **HOV/Carpool/Vanpool/Commuting Strategies** |
| HOV Lanes |
| HOV Lanes (24-hour applicability) |
| Car-Sharing |
| Employer-Based Commute Measures |
| **Regulatory Strategies** |
| Urban Nonmotorized Zones |
| Urban Parking Restrictions |
| **Systems Operations and Management Strategies** |
| Signal Management |
| Traveler Information |
| **Multimodal Freight Strategies** |
| Urban Consolidation Centers |


U.S. MID-RANGE ABATEMENT CURVE – 2030
Abatement cost <$50/ton
Cost
Real 2005 dollars per ton $CO_2e$
Potential
Gigatons/year
Residential electronics
Residential buildings – Lighting
Fuel economy packages – Light trucks
Commercial buildings – Combined heat and power
Industrial process improve-ments
Residential water heaters
Coal mining – Methane mgmt
Commercial buildings – Control systems
Residential buildings – Shell retrofits
Nuclear new-build
Active forest management
Coal power plants– CCS rebuilds with EOR
Distributed solar PV
Afforestation of cropland
Commercial buildings – HVAC equipment efficiency
Residential buildings – HVAC equipment efficiency
Solar CSP
Commercial electronics
Commercial buildings – LED lighting
Fuel economy packages – Cars
Commercial buildings – CFL lighting
Residential buildings – New shell improvements
Commercial buildings – New shell improvements
Cellulosic biofuels
Industry – Combined heat and power
Existing power plant conversion efficiency improvements
Conservation tillage
Manufacturing – HFCs mgmt
Onshore wind – Low penetration
Natural gas and petroleum systems management
Afforestation of pastureland
Reforestation
Winter cover crops
Onshore wind – Medium penetration
Coal power plants – CCS new builds with EOR
Biomass power – Cofiring
Onshore wind – High penetration
Coal power plants – CCS new builds
Industry – CCS new builds on carbon-intensive processes
Coal power plants – CCS rebuilds
Coal-to-gas shift – dispatch of existing plants
Car hybridi-zation
Source: McKinsey analysis

# Quick data analysis: by maximum GHG savings

```
> # summarize net GHG reductions
> dat %>%
+   group_by(Category) %>%
+   summarise(Exp = sum(Exp.GHG.red), Agg = sum(Agg.GHG.red), Max = sum(Max
+   arrange(desc(Max))
# A tibble: 9 x 4
  Category                                          Exp   Agg   Max
  <fct>                                           <dbl> <dbl> <dbl>
1 Pricing strategies                                 NA  8157 22339
2 Regulatory measures                              1318  2513  2793
3 System operations and management strategies        NA  1479  2219
4 HOV / carpool / vanpool / commute strategies      338   628  1471
5 Land use and smart growth strategies              160   865  1445
6 Public transportation strategies                  327   531  1014
7 Multimodal freight strategies                     241   336   494
8 Nonmotorized transportation strategies            133   288   403
9 Bottleneck relief and capacity expansion strategies  -7   -12   -26
```

# Quick data analysis: categorize by average GHG costs

```
> dat %>%
+   group_by(Category) %>%
+   summarise(Exp = sum(Exp.GHG.red)/sum(Exp.net.cost),
+             Agg = sum(Agg.GHG.red)/sum(Agg.net.cost),
+             Max = sum(Max.GHG.red)/sum(Max.net.cost) ) %>%
+   arrange(desc(Max))
# A tibble: 9 x 4
  Category                                           Exp      Agg      Max
  <fct>                                            <dbl>    <dbl>    <dbl>
1 Public transportation strategies                2.11     2.06     1.65
2 Bottleneck relief and capacity expansion strategies -0.0106 -0.00974 -0.0104
3 Land use and smart growth strategies            -1.37    -1.32    -1.32
4 Nonmotorized transportation strategies          -1.44    -1.50    -1.55
5 Regulatory measures                             -2.99    -2.85    -2.61
6 HOV / carpool / vanpool / commute strategies    18.4     -4.24    -3.02
7 Pricing strategies                              NA       -1.90    -6.09
8 System operations and management strategies     NA        7.52    -8.81
9 Multimodal freight strategies                   -9.13   -24      -73.6
```

# Quick data analysis: which specific strategies?

```
> dat %>%
+   select(Category, Strategy, Max.cost.p.mmt) %>%
+   arrange(desc(Max.cost.p.mmt)) %>%
+   print (n=50)
# A tibble: 47 x 3
   Category                                    Strategy                              Max.cost.p.mmt
   <fct>                                       <chr>                                          <dbl>
 1 System operations and management strategies Active traffic management                      6.20
 2 System operations and management strategies Integrated corridor management                 6.15
 3 System operations and management strategies Signal control management                      3.43
 4 Public transportation strategies            Intercity passenger rail                       2.76
 5 Multimodal freight strategies               Truck-only toll lanes                          2.10
 6 Regulatory measures                         Nonmotorized zones                             1.67
 7 Public transportation strategies            High-speed passenger rail                      1.38
 8 Pricing strategies                          Carbon pricing (VMT impact)                    1.12
 9 Public transportation strategies            Urban transit expansion                        0.982
10 Multimodal freight strategies               Marine system improvements                     0.769
11 System operations and management strategies Variable message signs                         0.682
12 HOV / carpool / vanpool / commute strategies HOV lanes                                     0.262
13 System operations and management strategies Vehicle infrastructure integration             0.192
14 System operations and management strategies Road weather management                        0.175
```

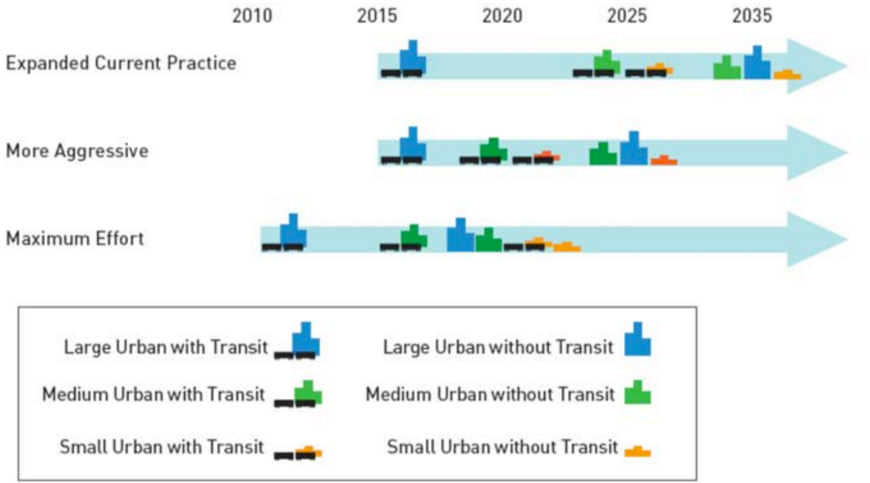
# Quick data analysis: which specific strategies?

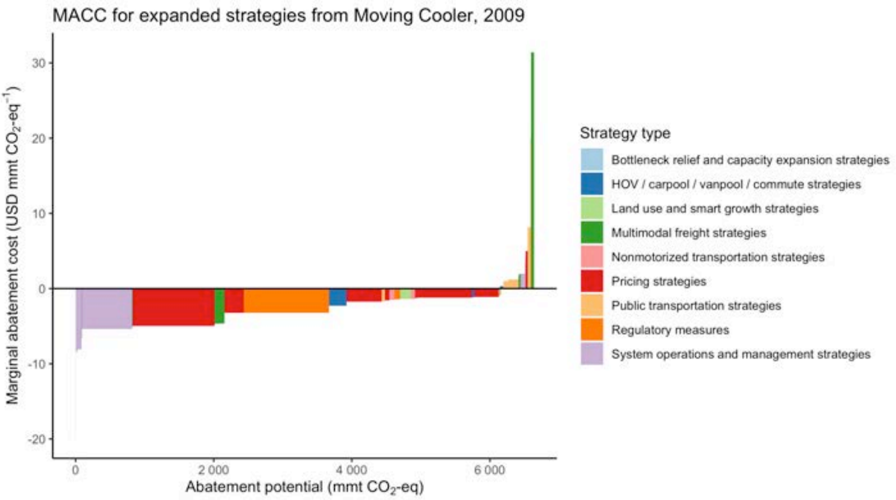
| | | | |
|---|---|---|---|
| 14 | System operations and management strategies | Road weather management | 0.175 |
| 15 | Bottleneck relief and capacity expansion strategies | Capacity expansion | -0.00796 |
| 16 | Bottleneck relief and capacity expansion strategies | Bottleneck relief | -0.0176 |
| 17 | Multimodal freight strategies | LCV permits | -0.875 |
| 18 | Public transportation strategies | Transit fare measures | -1.08 |
| 19 | Pricing strategies | PAYD | -1.08 |
| 20 | HOV / carpool / vanpool / commute strategies | Car-sharing | -1.11 |
| 21 | Pricing strategies | CBD / Activity Center on-street parking | -1.11 |
| 22 | Pricing strategies | Tax / higher tax on free private parking | -1.16 |
| 23 | Pricing strategies | VMT fee | -1.17 |
| 24 | Pricing strategies | Residential parking permits | -1.19 |
| 25 | Regulatory measures | Urban parking restrictions | -1.30 |
| 26 | Land use and smart growth strategies | Combined land use | -1.32 |
| 27 | HOV / carpool / vanpool / commute strategies | Employer-based commute strategies | -1.33 |
| 28 | Nonmotorized transportation strategies | Combined pedestrian | -1.46 |
| 29 | Pricing strategies | Cordon pricing | -1.57 |
| 30 | Nonmotorized transportation strategies | Combined bicycle | -1.67 |
| 31 | Pricing strategies | Congestion pricing | -1.90 |
| 32 | Pricing strategies | Intercity tolls | -2.13 |
| 33 | Regulatory measures | Speed limit reductions | -3.04 |

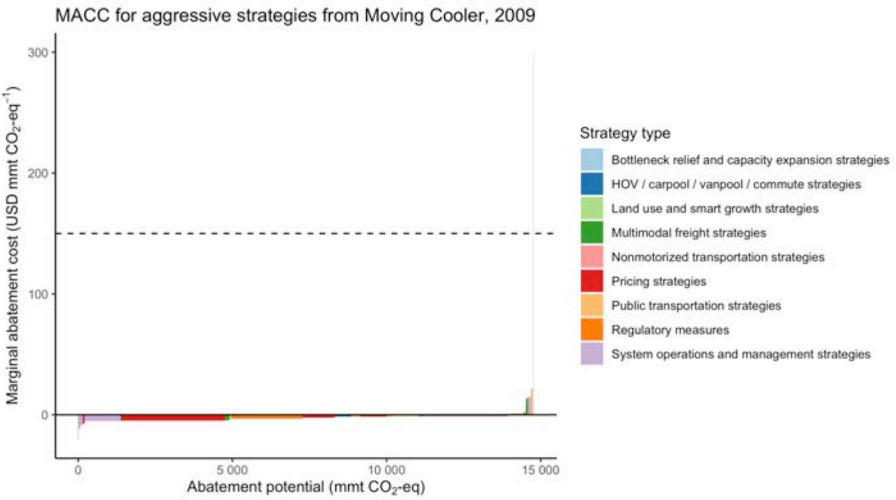
# Quick data analysis: which specific strategies?

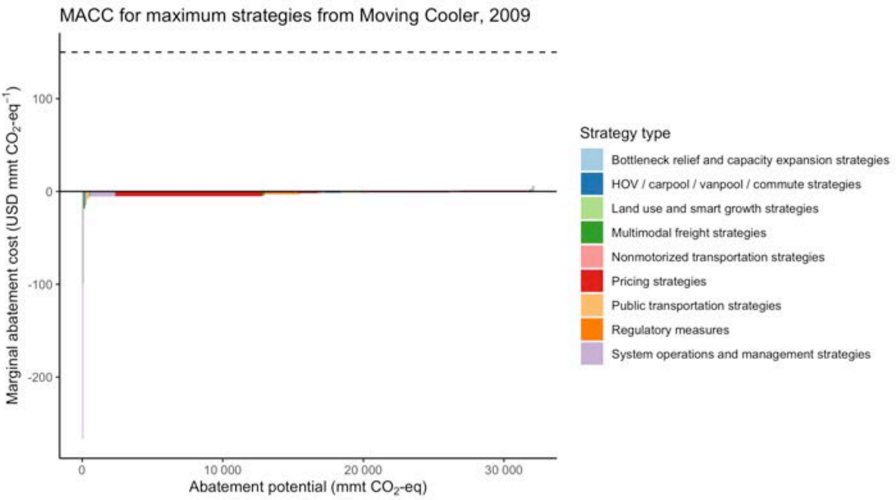
| | | | |
|---|---|---|---|
| 28 | Nonmotorized transportation strategies | Combined pedestrian | -1.46 |
| 29 | Pricing strategies | Cordon pricing | -1.57 |
| 30 | Nonmotorized transportation strategies | Combined bicycle | -1.67 |
| 31 | Pricing strategies | Congestion pricing | -1.90 |
| 32 | Pricing strategies | Intercity tolls | -2.13 |
| 33 | Regulatory measures | Speed limit reductions | -3.04 |
| 34 | Multimodal freight strategies | Urban consolidation centers | -3.33 |
| 35 | Multimodal freight strategies | Truck APUs | -4.49 |
| 36 | Multimodal freight strategies | Shipping container permits | -4.86 |
| 37 | Pricing strategies | Carbon pricing (fuel economy impact) | -4.92 |
| 38 | System operations and management strategies | Eco-driving | -5.39 |
| 39 | Multimodal freight strategies | Truck stop electrification | -5.54 |
| 40 | HOV / carpool / vanpool / commute strategies | HOV lanes (24-hour applicability) | -5.71 |
| 41 | Public transportation strategies | Transit frequency / LOS / Extent | -7.74 |
| 42 | System operations and management strategies | Traveler information | -9.69 |
| 43 | System operations and management strategies | Ramp metering | -14.6 |
| 44 | Multimodal freight strategies | Rail capacity improvements | -18.7 |
| 45 | Multimodal freight strategies | Weigh station bypass | -20 |
| 46 | Multimodal freight strategies | WIM screening | -100. |
| 47 | System operations and management strategies | Incident management | -267. |

# Expanded, aggressive, and maximum effort




MACC for expanded strategies from Moving Cooler, 2009
Marginal abatement cost (USD mmt CO2-eq-1)
30
20
10
0
-10
-20
0
2 000
4 000
6 000
Abatement potential (mmt CO2-eq)
Strategy type
Bottleneck relief and capacity expansion strategies
HOV / carpool / vanpool / commute strategies
Land use and smart growth strategies
Multimodal freight strategies
Nonmotorized transportation strategies
Pricing strategies
Public transportation strategies
Regulatory measures
System operations and management strategies


MACC for aggressive strategies from Moving Cooler, 2009
Marginal abatement cost (USD mmt CO2-eq-1)
300
200
100
0
0
5 000
10 000
15 000
Abatement potential (mmt CO2-eq)
Strategy type
Bottleneck relief and capacity expansion strategies
HOV / carpool / vanpool / commute strategies
Land use and smart growth strategies
Multimodal freight strategies
Nonmotorized transportation strategies
Pricing strategies
Public transportation strategies
Regulatory measures
System operations and management strategies


MACC for maximum strategies from Moving Cooler, 2009
Marginal abatement cost (USD mmt $CO_2$-eq$^{-1}$)
100
0
-100
-200
0
10 000
20 000
30 000
Abatement potential (mmt $CO_2$-eq)
Strategy type
Bottleneck relief and capacity expansion strategies
HOV / carpool / vanpool / commute strategies
Land use and smart growth strategies
Multimodal freight strategies
Nonmotorized transportation strategies
Pricing strategies
Public transportation strategies
Regulatory measures
System operations and management strategies

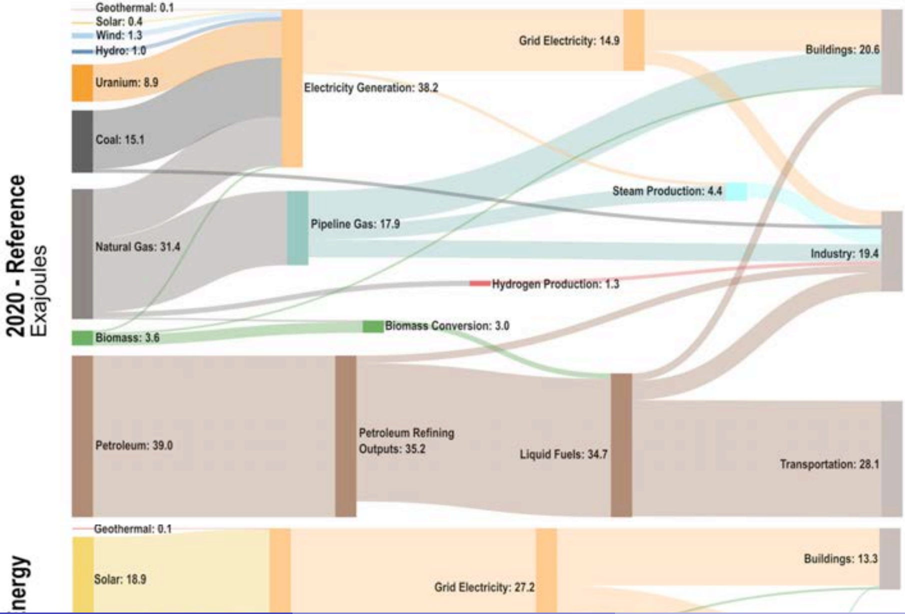
# Carbon emissions from transportation

Daniel Sperling from UC Davis has a nice way to think about this:

$$
\begin{array}{ll}
 & \texttt{Mobility (vehicle-miles-traveled)} \\
\times & \texttt{Vehicle energy efficiency (energy use / vehicle mile)} \\
\times & \texttt{Carbon intensity of energy (GHG / unit of energy)} \\
\hline
= & \texttt{GHG emissions}
\end{array}
$$

# Williams et al, 2020





# MIT CGC: Tough-to-decarbonize transport (T2DT) 2021

**Key finding: new vehicles, fuels & a new hydrogen (H2) system all necessary!**

- for low-GHG carbon-based fuels, main challenge is huge scale of fuel production
- all low-GHG fuel options (even biofuels) depend on huge-scale production of low-GHG H2
- cost of low-GHG H2 is often largest part of the cost of finished low-GHG fuel

# MIT CGC: Tough-to-decarbonize transport (T2DT) 2021

1. Long-distance vehicles carry energy, so energy density is crucial.
   - weight (& volume) of fuel or battery reduces payload
   - alternatives are 2-30x heavier (and bigger volume) than hydrocarbons
2. Scale
   - today only fossil fuels are available at the huge scale needed ($\sim$1 billion tons/year)
   - only a few low-carbon alternatives could reach needed scale by 2050
3. Existing vehicles are all designed to use hydrocarbon fuels
   - either need a carbon fuel that doesn't increase GHG, or new vehicles
   - vehicle lifetimes are long (20-30 years), new vehicle development is slow
4. Cost of the fuel is significant part of total cost of transport
   - currently fuels for this sector cost $1 Trillion/year
   - expensive infrastructure adds cost
5. Fuel infrastructure practicalities
   - room-temp liquid fuels easier to distribute & store than gases, solids
   - fast refueling/recharging is important for some vehicles.
   - need new fuel to be available at $\sim$800 ports, 17,000 airports, $>$100,000 truck stops

# MIT CGC: Tough-to-decarbonize transport (T2DT) 2021

| Sector | Trucking | Shipping | Aviation |
|---|---|---|---|
| Emissions | 1.25 Gt-CO2/yr | 1.0 Gt-CO2/yr | 1.0Gt-CO2/yr |
| Vehicle intensity | 1080 gCO2/km | 400 kgCO2/km | 125 gCO2/p-km |
| Engine intensity | 500 gCO2/kWh | 700 gCO2/kWh | 1500-2400 gCO2/kgfh |
| Main fuel | Diesel | Heavy fuel oil | Jet A |
| Main engine (power) | ICE, 300 kW | ICE, 10-100 MW | Gas turbines, 50-100 MW |
| State of EV | Available, but high cost | Very challenging for shipping | Impossible over long distances |
| Fuel cell option | High cost | High cost | Not possible |
| Viable pathways | Many | Carbon-based, ammonia, H2 | Carbon-based only |