Mobile Carbon Dioxide Removal: A Baseline Cost Estimate and Testing Protocol

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Vehicles are a significant source of emissions.
Transportation is the highest emitting sector through 2040
Carbon-fueled vehicles retain the highest market share through 2040.
Climate stabilization targets cannot be achieved without carbon dioxide removal from mobile emission sources!

But how do we accomplish this?
Approaches to carbon capture from stationary sources

Amine Solvents

Conventional or Novel Adsorbents (zeolites, activated carbons, MOFs)

Image from CO2CRC
Direct Air Capture is expensive

Image from Carbon Engineering; References: Socolow et al. 2011, House et al. 2011, Brandani 2012
Direct Air Capture is expensive

**Expected cost:**

> $600/tCO₂

- **10 times** the cost of capture from power plants

Image from Carbon Engineering; References: Socolow et al. 2011, House et al. 2011, Brandani 2012
Minimum work to separate increases as $\text{CO}_2$ concentration decreases

$$w_{\text{min,100\%}} = -\frac{RT}{y_A M_A} [y_A \ln(y_A) + (1 - y_A)\ln(1 - y_A)]$$
Minimum work to separate increases as CO$_2$ concentration decreases

\[ w_{\text{min,100\%}} = -\frac{RT}{y_A M_A} [y_A \ln(y_A) + (1 - y_A)\ln(1 - y_A)] \]
So let’s consider a mobile carbon capture system modeled along the lines of a stationary capture system…
Carbon Dioxide Removal from Mobile Emission Sources
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To capture the CO\textsubscript{2} emissions from 300 miles of driving in a light-duty vehicle, we need 650 kg of adsorbent with 20 wt% CO\textsubscript{2} capacity.

Mass requirements can be significantly decreased by changing several key conditions.
How do we offload CO$_2$ once it’s captured?
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Must decide:

1. where and when offloading occurs
2. what energy source is used
Where and when to offload CO$_2$?

Regeneration at Gas Station  
(travel distance = 300 mi)

Regeneration at Home  
(travel distance = 30 mi)
What energy source to use?

- **Power Plant or Renewables**
  - $0.10/kWh

- **Internal Combustion Engine**
  - $3/gallon
Cost categories and relevant assumptions

Weight/fuel penalty

Separation and compression

Capital costs

Transportation and storage
Cost categories and relevant assumptions

Weight/fuel penalty
  target fuel economy
  weight $\rightarrow$ miles per gallon
  45 mpg
  7% ↓ in mpg per 10% ↑ in mass

Separation and compression

Capital costs

Transportation and storage
## Cost categories and relevant assumptions

### Weight/fuel penalty
- target fuel economy: 45 mpg
- weight → miles per gallon: 7% ↓ in mpg per 10% ↑ in mass

### Separation and compression
- $\eta_{\text{II}}$ separation/compression: 0.40 / 0.85
- carbon intensity of electricity: 0.5 kg/ kWh

### Capital costs

### Transportation and storage
## Cost categories and relevant assumptions

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Assumptions</th>
</tr>
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<tbody>
<tr>
<td>Weight/fuel penalty</td>
<td>target fuel economy: weight (\rightarrow) miles per gallon</td>
<td>45 mpg, 7% (\downarrow) in mpg per 10% (\uparrow) in mass</td>
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<td>Transportation and storage</td>
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\(\eta_{\text{II}}\) refers to the efficiency of separation/compression.
Cost categories and relevant assumptions

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<td>100% separation and compression costs</td>
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<tr>
<td>Transportation and storage</td>
<td>pipeline transport</td>
<td>$2/tonne</td>
</tr>
<tr>
<td></td>
<td>distance</td>
<td>100 km</td>
</tr>
<tr>
<td></td>
<td>CO$_2$ emissions</td>
<td>0.005 kg/tonne-km</td>
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<tr>
<td></td>
<td>storage</td>
<td>$13/tonne</td>
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Cost estimate for mobile capture scenarios

![Diagram showing cost estimates for different factors related to mobile capture scenarios. The diagram includes categories such as Offloading Frequency, Energy Source, Transport and Storage, Capital Costs, Separation/Compression, and Weight/Fuel Penalty. It displays a range of costs per tonne CO₂ avoided, from $0 to $500.](image-url)
Cost estimate for mobile capture scenarios
Cost estimate for mobile capture scenarios

Offloading Frequency | Energy Source
--- | ---
Petrol | Petrol
Petrol | Electricty
House | Diesel

- Transport and Storage
- Capital Costs
- Separation/Compression
- Weight/Fuel Penalty

$/tonne CO₂ avoided
Cost estimate for mobile capture scenarios

Offloading Frequency | Energy Source
---|---
| Petrol + | Capital Costs |
| Petrol + + | Separation/ Compression |
| + + + | Weight/Fuel Penalty |

$/tonne CO₂ avoided

- Transport and Storage
- Capital Costs
- Separation/ Compression
- Weight/Fuel Penalty
What does this mean for you?

Average car emissions: 6 tons CO₂ per year

Price of CO₂ abatement: $70/t

Annual cost to capture emissions:
What does this mean for you?

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Price of CO₂ abatement: $70/t

Annual cost to capture emissions: $420
Almost equal share of emissions from heavy duty and light duty vehicles

GLOBAL ANTHROPOGENIC EMISSIONS
≈ 38 Gt CO₂

TRANSPORT EMISSIONS
≈ 8.8 Gt CO₂

ROAD TRANSPORT EMISSIONS
≈ 6.5 Gt CO₂

Other 77%
Transport 23%

4.6%
10.6%
73.9%
10.9%

46.5%
53.5%
Almost equal share of emissions from heavy duty and light duty vehicles

Travel distance/regeneration period: 250 mi (400 km)
Target fuel economy: 6.8 mpg
CO₂ capture from heavy duty vehicles is comparable with light duty best case scenario.
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New annual shipping premium: $12.60
MCDR costs are on par with other carbon capture methods and significantly less than DAC.
Testing protocol permits comprehensive evaluation of material performance.
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Static (@ 298-343K) → Dynamic, N₂-CO₂ blend → Dynamic, exhaust blend → Dynamic, wet exhaust blend —
Testing protocol permits comprehensive evaluation of material performance

Static (at 298-343K) → Dynamic, N₂-CO₂ blend → Dynamic, exhaust blend → Dynamic, wet exhaust blend → Proof-of-concept (1:4 scale) using actual exhaust
Conclusions and next steps

- Mobile carbon dioxide removal is theoretically feasible and economical
  - Especially when compared to direct air capture
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