LIFE CYCLE ANALYSIS OF HEAVY-DUTY TRUCKS

An environmental impact study comparing alternative fuels/drivetrains

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RESEARCH PROBLEM & FUNCTIONAL UNIT

• THE question: which type of engine/powertrain has the lowest carbon footprint? Electric (EV) or hydrogen fuel cell (FCV)?

• Understand the life cycle impacts from all phases of alternative technology heavy-duty trucks
  • Compare all phases of the lifecycle including the manufacturing, distribution, operation, and retirement/recycling of truck components which are different between models, not those items which are the same (e.g., a tire is a tire) → changed to entire vehicle comparison

• Functional unit = 1 mile driven

• Main assumptions
  • Both class-8 trucks used in same region with same number of miles (48,360/yr., 10-year life, 300-mile range)
  • Information on vehicles gleamed from various sources since not in production
    • Kenworth/Toyota T680 in demonstration (CARB grant)
    • Tesla running tests, but access to test Semi not available to outside entities
SYSTEM FLOW DIAGRAM & BOUNDARY (EV AND FCV)

Raw material extraction
metals, non-metals, metalloids
Energy for mining/brine lakes

Natural resources

Material production (separation, concentration, primary refining, chemical refining)

Component fabrication & subassembly (high-voltage lithium-ion batteries, inverter, electric motor, fuel cells)

Truck final assy at OEM

Factory to dealer to fleet

Product use

End of life

Ops/Maint. Natural Gas, Grid, Solar

H production

BET

FCET

recycle/reuse/dispose

Transportation
energy (grid, solar)
water
emissions, toxic pollutants
landfill

Reuse of high value elements or battery units for grid storage systems

Low value elements
TOOLS: AFLEET 2020 & GREET 2020

- By Argonne National Library; gold standard for vehicle emission modelling. FREE!

- **Alternative Fuel Life-Cycle Environmental and Economic Transportation**
  - Estimates energy use, GHG emissions, and air pollutants emissions for alternative fuel light and heavy-duty vehicles
  - Well-to-wheels (WTW) phases = wheel to pump (fuel cycle) + pump to wheels (use cycle)

- **Greenhouse Gases, Regulated Emissions, and Energy use in Technologies**
  - Estimates energy use, GHG emissions, and air pollutants emissions for passenger vehicles
  - Vehicle cycle + recycling phases
    - Raw material recovery/transport/processing
    - Material production/processing
    - Vehicle assembly
    - Disposal/recycling of vehicle; battery recycling (new addition)

https://greet.es.anl.gov/
LCA PROCESS

Inventory Analysis
• Obtain data for major component systems with differences
• Determine scale up ratios for car to truck conversion

AFLEET
• Heavy-duty truck app
• Well to pump (fuel cycle) & pump to wheel (use cycle) modeling

GREET
• Passenger vehicle app
• Cradle to gate phases + recycling/disposal modeling
• “Factor up” for trucks

Synthesize/Normalize
• Combine all phases in Excel
• Adjust to functional unit
## MODEL DATA INPUTS

<table>
<thead>
<tr>
<th>type</th>
<th>component</th>
<th>car</th>
<th>truck</th>
<th>factor</th>
<th>factor based on</th>
<th>references/notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>diesel</td>
<td>model</td>
<td>GREET default</td>
<td>Kenworth/Toyota T680</td>
<td>4.46</td>
<td>weight</td>
<td>GREET, Truckinginf</td>
</tr>
<tr>
<td></td>
<td>vehicle weight</td>
<td>3184 lbs.</td>
<td>14200 lbs.</td>
<td>4.46</td>
<td>weight</td>
<td></td>
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<tr>
<td>EV</td>
<td>model</td>
<td>Tesla Model S (2021 model)</td>
<td>Tesla Semi</td>
<td>5.64</td>
<td>weight</td>
<td>Tesla, Teslarati</td>
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<tr>
<td></td>
<td>vehicle weight</td>
<td>4766 lbs.</td>
<td>26909 lbs.</td>
<td>5.64</td>
<td>weight</td>
<td></td>
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<tr>
<td></td>
<td>lithium-ion battery NCA</td>
<td>85 kWh, 1200 lbs. (7104 cells)</td>
<td>500 kWh, 5622 lbs.</td>
<td>5.88</td>
<td>kWh</td>
<td>Electrek, Insideevs.news, Teslarati</td>
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<tr>
<td></td>
<td>motor</td>
<td>2 ea. (70 lbs./140 lbs.)</td>
<td>4 ea.</td>
<td>2</td>
<td>quantity</td>
<td>Tesla</td>
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<tr>
<td></td>
<td>power converter</td>
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<td>--</td>
<td>5.64</td>
<td>overall weight</td>
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<tr>
<td>FCV</td>
<td>model</td>
<td>Mirai (2021 model)</td>
<td>Kenworth/Toyota T680 FCV</td>
<td>5.17</td>
<td>weight</td>
<td>Autolog, CCJ Digital</td>
</tr>
<tr>
<td></td>
<td>vehicle weight</td>
<td>4255 lbs. (XLE 4 dr model)</td>
<td>22000 lbs.</td>
<td>5.17</td>
<td>weight</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fuel cell stack</td>
<td>1 ea. 128 kw, 172 hp; 25.5 kg</td>
<td>2 ea. 153 hp</td>
<td>1.779</td>
<td>hp</td>
<td>Fuelcellworks, Toyota, Greencar Reports</td>
</tr>
<tr>
<td></td>
<td>fuel tanks</td>
<td>3 ea.; 5.6 kg capacity; 131 kg</td>
<td>6 ea.; 60 kg capacity (no wt)</td>
<td>10.714</td>
<td>capacity*</td>
<td>Fuelcellworks, Greencar Reports</td>
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<tr>
<td></td>
<td>lithium-ion battery NCA</td>
<td>1.24 kWh (84 cells); 44.6 kg</td>
<td>12 kWh; 907 kg</td>
<td>9.677</td>
<td>kWh</td>
<td>Car &amp; Driver, CCJ Digital, Greencar Reports</td>
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<tr>
<td></td>
<td>tractor motor</td>
<td>1325 torque, 670 hp</td>
<td>221 torque, 182 hp</td>
<td>3.68</td>
<td>hp</td>
<td>Motortrend, Fleet Equipment</td>
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<tr>
<td></td>
<td>power converter</td>
<td>25.5 kg</td>
<td>--</td>
<td>5.17</td>
<td>overall weight</td>
<td>Fuelcellworks</td>
</tr>
</tbody>
</table>

*Factor adjusted to overall weight since % of tank to vehicle allocation > than calculated
MODEL DATA INPUTS

- GREET presents data for total life of vehicle
- AFLEET presents data for yearly and total life of vehicle
- Adjusted to functional unit (1 mile) for all

**CO2e calculation (per IPCC 2nd assessment Rpt)**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Factor</th>
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<tbody>
<tr>
<td>CO2</td>
<td>1</td>
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<tr>
<td>CH4</td>
<td>21</td>
</tr>
<tr>
<td>N2O</td>
<td>310</td>
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</tbody>
</table>

**Western Electricity Coordinating Council (WECC) Mix**

<table>
<thead>
<tr>
<th>Year</th>
<th>Residual Oil</th>
<th>Natural Gas</th>
<th>Coal</th>
<th>Nuclear</th>
<th>Biomass</th>
<th>Hydroelectric</th>
<th>Geothermal</th>
<th>Wind</th>
<th>Solar PV</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>0.14%</td>
<td>31.24%</td>
<td>17.38%</td>
<td>8.40%</td>
<td>0.45%</td>
<td>25.58%</td>
<td>2.26%</td>
<td>7.65%</td>
<td>6.50%</td>
<td>0.40%</td>
</tr>
</tbody>
</table>
RESULTS: ENERGY & CO2e COMPARISONS

**Total Energy Life Cycle Comparison FU = 1 mile**

- FCV (solar)
- FCV (SMR)
- EV
- Diesel

**CO2e (g) Life Cycle Comparison FU = 1 mile**

- FCV (solar)
- FCV (SMR)
- EV
- Diesel
RESULTS: VOC, CO, NOx, PM, SOx COMPARISONS

Emission (g) comparison between trucks
All phases, FU = 1 mile
COMPARE DIFFERENCE FOR ALTERNATIVE METHOD OF H2 PRODUCTION
<table>
<thead>
<tr>
<th>Impact categories</th>
<th>impact factor</th>
<th>emission/use</th>
<th>notes</th>
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</thead>
<tbody>
<tr>
<td>climate change</td>
<td>21.5</td>
<td>CO2e (CO2, CH4, N2O)</td>
<td></td>
</tr>
<tr>
<td>photochemical ozone formation</td>
<td>2.4</td>
<td>VOC, NOx, CO</td>
<td></td>
</tr>
<tr>
<td>acidification</td>
<td>1.5</td>
<td>NOx, SOx</td>
<td></td>
</tr>
<tr>
<td>terrestrial eutrophication</td>
<td>1.0</td>
<td>NOx</td>
<td></td>
</tr>
<tr>
<td>particulate matter</td>
<td>0.1</td>
<td>PM2.5 (PM10 excluded)</td>
<td></td>
</tr>
<tr>
<td>resource depletion</td>
<td>18.6 (m³)</td>
<td>water resource depletion</td>
<td>* gallons by 0.00378541178</td>
</tr>
<tr>
<td>mineral resource depletion</td>
<td>12.7</td>
<td>&lt;did not include&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>Diesel</th>
<th>EV</th>
<th>FVC (SMR)</th>
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</thead>
<tbody>
<tr>
<td>climate change</td>
<td>43,655.568</td>
<td>15,481.854</td>
<td>55,740.216</td>
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<td>photochemical ozone formation</td>
<td>14.507</td>
<td>3.941</td>
<td>5.943</td>
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<td>acidification</td>
<td>5.733</td>
<td>5.613</td>
<td>3.729</td>
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<td>terrestrial eutrophication</td>
<td>3.414</td>
<td>0.610</td>
<td>1.005</td>
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<tr>
<td>particulate matter</td>
<td>0.008</td>
<td>0.008</td>
<td>0.012</td>
</tr>
<tr>
<td>resource depletion</td>
<td>0.000</td>
<td>0.001</td>
<td>0.001</td>
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<tr>
<td>mineral resource depletion</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>43,679.230</td>
<td>15,492.026</td>
<td>55,750.906</td>
</tr>
</tbody>
</table>

JUST TO PUT THINGS IN CONTEXT...

FOR USE PHASE INCLUDING FUEL CYCLE
LIMITATIONS

• Manufacturing info not available for these new technologies
• “Black boxes” at their finest
• Highly complex, but did allow for one to customize inputs (if you had that level of detail)
• Did not provide references consistently where information was obtained from
• The manuals/user guides are lacking but getting better!
• EOL recycling of batteries is still in its infancy; only high value elements are extracted and reused. The battery recycling is new for 2020 and needs work.
• Wanted to compare just those components of interest; this tool does not allow for that since materials are spread among all categories
• Would like to have further breakdown of phases – this is possible, but will take a lot of manipulation of the tool
• Did not include charging infrastructure at site but tool supports doing it
• CO2e I found was not current in the tools, so I adjusted to IPCC 100 yrs.
• H2O consumption for hydrogen production needs more study
• Raw materials or components – could not specify source
NEXT STEPS

- Recheck hydrogen scale up by talking with experts; adjust as necessary
- Run model with current & future CA grid, EIA region mix with more fossil fuels
- Add natural gas truck to mix

Source: GREET
Thank you!