Light-duty Plug-in Electric Vehicles in NETPLAN

Di Wu          Dr. Dionysios Aliprantis          Dr. Konstantina Gkritza

IOWA STATE UNIVERSITY

NETSCORE21
Research Project

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Outline of Topics

1. Objective
2. NETPLAN formulation
3. Electric power & energy consumption from PEVs
4. Modeling methods
Objective

Transportation demand:

- freight
- passenger
  - personal light-duty vehicles
  - airplanes
  - trains
  - others

Detailed method, discussion, and relevant data can be found at http://home.eng.iastate.edu/~dwu/PEV_NETPLAN.html
\[
\text{min} \ \{ \text{CostOp}^E + \text{CostInv}^E + \text{CostOp}^T + \text{CostFleetInv}^T + \text{CostInfInv}^T \} \\
\text{subject to:}
\]
- Meet energy demand at every node
  \[
  \sum_t \eta(i,j) e(i,j)(t) - \sum_t e_{\text{in}}(i,j)(t) = d_j^E(t) + d_j^{\text{ET}}(t) \quad (1b)
  \]
- Energy flow lower and upper bounds
  \[
  l_b e(i,j)(t) \leq e(i,j)(t) \leq u_b e(i,j)(t) \Delta t + \sum_{z=0}^{t} e_{\text{inf}}(i,j)(z) \Delta z \quad (1c)
  \]
- DC power flow equations
  \[
  e(i,j)(t) = b(i,j) \left( \theta_i(t) - \theta_j(t) \right), \quad \forall (i,j) \in A^E_{DC} \quad (1d)
  \]
- Transportation demand for non-energy commodities
  \[
  \sum_{m} f_{i,j,k,m}(t) = d_{i,j,k}(t), \quad k \in K \setminus K_c \quad (1e)
  \]
- Transportation demand for energy commodities
  \[
  \sum_{m} f_{i,j,k,m}(t) = \text{heatContent}^{-1}(t) e(n_{i,j,k},n_{i,j,k})(t), \quad k \in K_c \quad (1f)
  \]
- Fleet upper bound for transportation flows
  \[
  \sum_k f_{i,j,k,m}(t) \leq \text{ubFleet}_{i,j,m}(t) \Delta t + \sum_{z=0}^{t} \text{fleet}_{i,j,m}(z) \Delta z \quad (1g)
  \]
- Infrastructure upper bound for transportation flows
  \[
  \sum_k \sum_{m \in M_i} f_{i,j,k,m}(t) \leq \text{ubInf}_{i,j,l}(t) \Delta t + \sum_{z=0}^{t} \text{inf}_{i,j,l}(z) \Delta z \quad (1h)
  \]

where:
- \( \text{CostOp}^E = \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costOp}^E_{i,j}(t) e_{i,j}(t) \quad (1i) \)
- \( \text{CostInv}^E = \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costInv}^E_{i,j}(t) e_{i,j}(t) \quad (1j) \)
- \( \text{CostOp}^T = \sum_t \sum_{(i,j,k,m)} (1 + r)^{-t} \text{costOp}^T_{i,j,k,m}(t) f_{i,j,k,m}(t) \quad (1k) \)
- \( \text{CostFleetInv}^T = \sum_t \sum_{(i,j,m)} (1 + r)^{-t} \text{costFleetInv}^T_{i,j,m}(t) \quad (1l) \)
- Energy flow lower and upper bounds
- \( \text{CostInfInv}^T = \sum_t \sum_{(i,j,l)} (1 + r)^{-t} \text{costInfInv}^T_{i,j,l}(t) \quad (1m) \)

Decision variables:
- Energy flows: \( e_{i,j}(t) \geq 0 \quad (1o) \)
- Energy capacity inv.: \( l_b e_{i,j}(t) \leq e_{\text{in}}_{i,j}(t) \leq u_b e_{i,j}(t) \quad (1p) \)
- Transportation flows: \( f_{i,j,k,m}(t) \geq 0 \quad (1q) \)
- Fleet inv.: \( l_b \text{Fleet}_{i,j,m}(t) \leq \text{Fleet}_{i,j,m}(t) \leq u_b \text{Fleet}_{i,j,m}(t) \quad (1r) \)
- Infrastructure inv.: \( l_b \text{Inf}_{i,j,l}(t) \leq \text{Inf}_{i,j,l}(t) \leq u_b \text{Inf}_{i,j,l}(t) \quad (1s) \)
- Phase angles: \( -\pi \leq \theta_i(t) \leq \pi \quad (1t) \)
NETPLAN formulation

\[
\begin{align*}
\text{min} \quad & \{ \text{CostOp}^E + \text{CostInv}^E + \text{CostOp}^T + \text{CostFleetInv}^T + \text{CostInfInv}^T \} \quad (1a) \\
\text{subject to:} \\
& \text{Meet energy demand at every node} \\
& \sum_i \eta_{(i,j)}(t)e_{(i,j)}(t) - \sum_i e_{(i,j)}(t) = d_j^E(t) + d_j^{ET}(t) \quad (1b) \\
& \text{Energy flow lower and upper bounds} \\
& l_b e_{(i,j)}(t) \leq e_{(i,j)}(t) \leq u_b e_{(i,j)}(t) \Delta t + \sum_{z=0}^t e_{(i,j)}(z) \Delta z \quad (1c) \\
& \text{DC power flow equations} \\
& e_{(i,j)}(t) = b_{(i,j)}(\theta_i(t) - \theta_j(t)), \quad \forall (i, j) \in \mathcal{A}_E^E \quad (1d) \\
& \text{Transportation demand for non-energy commodities} \\
& \sum_{m} f_{(i,j,k,m)}(t) = d_{(i,j,k)}^T(t), \quad k \in K \setminus K_c \quad (1e) \\
& \text{Transportation demand for energy commodities} \\
& \sum_{m} f_{(i,j,k,m)}(t) = \text{heatContent}^k(t) e_{(n_{(i,j,k)},n_{(i,j,k)})}(t), \quad k \in K_c \quad (1f) \\
& \text{Fleet upper bound for transportation flows} \\
& \sum_k f_{(i,j,k,m)}(t) \leq u_b \text{Fleet}_{(i,j,m)}(t) \Delta t + \sum_{z=0}^t \text{FleetInv}_{(i,j,m)}(z) \Delta z \quad (1g) \\
& \text{Infrastructure upper bound for transportation flows} \\
& \sum_k \sum_{m \in M_l} f_{(i,j,k,m)}(t) \leq u_b \text{Inf}_{(i,j,l)}(t) \Delta t + \sum_{z=0}^t \text{Inf}_{(i,j,l)}(z) \Delta z \quad (1h) \\
\end{align*}
\]

where:

\[
\begin{align*}
\text{CostOp}^E &= \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costOp}_{(i,j)}^E(t) e_{(i,j)}(t) \quad (1i) \\
\text{CostInv}^E &= \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costInv}_{(i,j)}^E(t) \text{eInv}_{(i,j)}(t) \quad (1j) \\
\text{CostOp}^T &= \sum_t \sum_{(i,j,k,m)} (1 + r)^{-t} \text{costOp}_{(i,j,k,m)}^T(t) f_{(i,j,k,m)}(t) \quad (1k) \\
\text{CostFleetInv}^T &= \sum_t \sum_{(i,j,k,m)} (1 + r)^{-t} \text{costFleetInv}_{(i,j,m)}(t) \text{fleetInv}_{(i,j,m)}(t) \quad (1l) \\
\text{CostInfInv}^T &= \sum_t \sum_{(i,j,l)} (1 + r)^{-t} \text{costInf}_{(i,j,l)}^T(t) \text{infInv}_{(i,j,l)}(t) \quad (1m) \\
\end{align*}
\]

Energy demand from the transportation system

\[
\begin{align*}
d_j^{ET}(t) &= \sum_{(a,b) \in \mathcal{A}_E^T} \sum_m \text{fuelCons}_{(a,b,m)}(t) \sum_k f_{(a,b,k,m)}(t) \quad (1n) \\
\end{align*}
\]

Decision variables:

- Energy flows: \( e_{(i,j)}(t) \geq 0 \) \hspace{1cm} (1o)
- Energy capacity inv.: \( l_b \text{Inv}_{(i,j)}(t) \leq \text{Inv}_{(i,j)}(t) \leq u_b \text{Inv}_{(i,j)}(t) \) \hspace{1cm} (1p)
- Transportation flows: \( f_{(i,j,k,m)} \geq 0 \) \hspace{1cm} (1q)
- Fleet inv.: \( l_b \text{Fleet}_{(i,j,m)}(t) \leq \text{Fleet}_{(i,j,m)}(t) \leq u_b \text{Fleet}_{(i,j,m)}(t) \) \hspace{1cm} (1r)
- Infrastructure inv.: \( l_b \text{Inf}_{(i,j,l)}(t) \leq \text{Inf}_{(i,j,l)}(t) \leq u_b \text{Inf}_{(i,j,l)}(t) \) \hspace{1cm} (1s)
- Phase angles: \(-\pi \leq \theta_i(t) \leq \pi\) \hspace{1cm} (1t)

- \textbf{CostOp}^E and \textbf{CostInv}^E
- \textbf{CostOp}^T
- \textbf{CostFleetInv}^T
- \textbf{CostInfInv}^T
The tractive energy per mile that is provided by the battery in charge-depleting mode ($h_e$) is a fraction ($\xi$) of total tractive energy per mile ($h_{tr}$): $h_e = \xi h_{tr}$.

Source: M. Duoba, 2005, Argonne National Lab
### Assumptions

1. Tractive energy per mile ($h_{tr}$) is a normal distribution with mean determined by vehicle class as shown below, and standard deviation equal to 10% of its mean.

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Car</th>
<th>Van</th>
<th>SUV</th>
<th>Pickup truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(h_{dr})$ (kWh/mile)</td>
<td>0.21</td>
<td>0.33</td>
<td>0.37</td>
<td>0.40</td>
</tr>
</tbody>
</table>

2. Fraction of tractive energy derived from electricity ($\xi$):

$$f_{\xi}(x) = \begin{cases} 
1 & \text{for } 0.2 \leq x < 1, \\
0.2\delta(x-1) & \text{for } x = 1.
\end{cases}$$

3. Charge-depleting range ($d$): log-normal distribution function with expected value and standard deviation equal to (40,10) and (70,20).

4. $\eta$ is assumed to be constant and equal to 0.672.
Charging scenarios

Two uncontrolled charging scenarios are simulated:

(A) charging any time the vehicle is parked at home
(B) “opportunistic” charging at any location (home, shopping mall, work, etc.)

Typical Charging Circuits

<table>
<thead>
<tr>
<th>Charging circuit</th>
<th>Charger size (kW)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 V, 15 A (Level 1)</td>
<td>1.4</td>
<td>1/3</td>
</tr>
<tr>
<td>120 V, 20 A (Level 1)</td>
<td>2</td>
<td>1/3</td>
</tr>
<tr>
<td>240 V, 30 A (Level 2)</td>
<td>6</td>
<td>1/3</td>
</tr>
</tbody>
</table>
Simulation with example data

The 2009 NHTS collects information on the travel behavior of a national representative sample of U.S. households, such as mode of transportation, trip origin and purpose, and trip distance. The survey consists of 150,147 households and 294,408 Light-Duty Vehicles (LDVs).

Data Example from the 2009 NHTS

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type</th>
<th>Origin/purpose</th>
<th>Start time</th>
<th>Destination/purpose</th>
<th>End time</th>
<th>Trip miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Veh1</td>
<td>Car</td>
<td>Home</td>
<td>07:30</td>
<td>Work</td>
<td>07:40</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Work</td>
<td>16:30</td>
<td>Home</td>
<td>16:40</td>
<td>2</td>
</tr>
<tr>
<td>Veh2</td>
<td>SUV</td>
<td>Home</td>
<td>07:30</td>
<td>Work</td>
<td>07:45</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Work</td>
<td>17:30</td>
<td>Home</td>
<td>17:45</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Home</td>
<td>19:20</td>
<td>Shopping</td>
<td>19:35</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shopping</td>
<td>21:10</td>
<td>Home</td>
<td>21:25</td>
<td>4</td>
</tr>
</tbody>
</table>

Veh 1 in Scenario (A) with 2-kW charger

Veh 2 in Scenario (B) with mixed chargers
Modeling methods

- the interdependency between the charge-depleting range (CDR) and the travel pattern
- the number of new sale light-duty vehicles \( N^{\text{sale}}_{LV}(t) \), where \( LV \in \{CV, HEV, d_1, d_2, \ldots, d_n\} \) as decision variables

Four cases: 0.0, 0.1, 1.0, 1.1
Model 0.0

\[
\text{min } \{ \text{CostOp}^E + \text{CostInv}^E + \text{CostOp}^T + \text{CostFleetInv}^T + \text{CostInfInv}^T \} \\
\text{subject to:}
\]

Meet energy demand at every node
\[
\sum_i \eta_{i,j}(t)e_{i,j}(t) - \sum_i e_{i,j}(t) = d_j^E(t) + d_j^{ET}(t)
\] (1a)

Energy flow lower and upper bounds
\[
lb_{i,j}(t) \leq e_{i,j}(t) \leq ub_{i,j}(t) \Delta t + \sum_{z=0}^t e_{i,j}(z) \Delta z
\] (1b)

Phase angles
\[
-\pi \leq \theta_i(t) \leq \pi
\] (1c)

DC power flow equations
\[
e_{i,j}(t) = b_{i,j}(\theta_i(t) - \theta_j(t)), \quad \forall (i,j) \in A^\text{D}
\] (1d)

Transportation demand for non-energy commodities
\[
\sum_m f_{i,j,k,m}(t) = d_{i,j,k}(t), \quad k \in K \setminus K_c
\] (1e)

Transportation demand for energy commodities
\[
\sum_m f_{i,j,k,m}(t) = \text{heatContent}_{i,k}(t) e_{i,j}(t), \quad k \in K_c
\] (1f)

Fleet upper bound for transportation flows
\[
\sum_k f_{i,j,k,m}(t) \leq \text{ubFl}_{i,j,m}(t) \Delta t + \sum_{z=0}^t \text{Inf}_{i,j}(z) \Delta z
\] (1g)

Infrastructure upper bound for transportation flows
\[
\sum_k \sum_{m \in M_j} f_{i,j,k,m}(t) \leq \text{ubInf}_{i,j,t}(t) \Delta t + \sum_{z=0}^t \text{inf}_{i,j}(z) \Delta z
\] (1h)

where:

\[
\text{CostOp}^E = \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costOp}^E_{i,j}(t) e_{i,j}(t)
\] (1i)

\[
\text{CostInv}^E = \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costInv}^E_{i,j}(t) e_{i,j}(t)
\] (1j)

\[
\text{CostOp}^T = \sum_t \sum_{(i,j,k,m)} (1 + r)^{-t} \text{costOp}^T_{i,j,k,m}(t) f_{i,j,k,m}(t)
\] (1k)

\[
\text{CostFleetInv}^T = \sum_t \sum_{(i,j,k,m)} (1 + r)^{-t} \text{costFleetInv}^T_{i,j,k,m}(t) \text{fleet}_{i,j,k,m}(t)
\] (1l)

\[
\text{CostInfInv}^T = \sum_t \sum_{(i,j,t)} (1 + r)^{-t} \text{costInfInv}^T_{i,j,t}(t) \text{inf}_{i,j}(t)
\] (1m)

Energy demand from the transportation system
\[
\text{d}_{j}^{ET}(t) = \sum_{(a,b) \in A^G_j} \sum_{m \in M_j} \text{fuelCost}_{i, a,b,m}(t) \sum_k f_{i,j,k,m}(t) + d_{j}^{ET}(t)
\] (1n)

Decision variables:

Energy flows
\[
e_{i,j}(t) \geq 0
\] (1o)

Energy capacity inv.
\[
\text{lbFl}_{i,j}(t) \leq \text{Fl}_{i,j}(t) \leq \text{ubFl}_{i,j}(t)
\] (1p)

Transportation flows
\[
f_{i,j,k,m}(t) \geq 0
\] (1q)

Fleet inv.
\[
\text{lbFl}_{i,j,k,m}(t) \leq \text{Fl}_{i,j,k,m}(t) \leq \text{ubFl}_{i,j,k,m}(t)
\] (1r)

Infrastructure inv.
\[
\text{lbFl}_{i,j,t}(t) \leq \text{Fl}_{i,j,t}(t) \leq \text{ubFl}_{i,j,t}(t)
\] (1s)

Phase angles
\[
-\pi \leq \theta_i(t) \leq \pi
\] (1t)
Model 0.0

\[
\min \left\{ \text{CostOp}^E + \text{CostInv}^E + \text{CostOp}^T + \text{CostFleetInv}^T + \text{CostInfInv}^T \right\} \quad (1a)
\]

subject to:

Meet energy demand at every node

\[
\sum_i \eta_{i,j}(t) e_{i,j}(t) - \sum_i e_{i,j}(t) = d_j^E(t) + d_j^{ET}(t) \quad (1b)
\]

Energy flow lower and upper bounds

\[
lbe_{i,j}(t) \leq e_{i,j}(t) \leq ube_{i,j}(t) \Delta t + \sum_{z=0}^t \Delta z \quad (1c)
\]

DC power flow equations

\[
e_{i,j}(t) = b_{i,j} \left( \theta_i(t) - \theta_j(t) \right), \quad \forall (i, j) \in A^E_{DC} \quad (1d)
\]

Transportation demand for non-energy commodities

\[
\sum_m f_{i,j,k,m}(t) = d_{i,j,k}(t), \quad k \in K \smallsetminus K_c \quad (1e)
\]

Transportation demand for energy commodities

\[
\sum_m f_{i,j,k,m}(t) = \text{heatContent}\_k^{-1}(t) e_{a_{i,j},b_{i,j}}(t), \quad k \in K_c \quad (1f)
\]

Fleet upper bound for transportation flows

\[
\sum_k f_{i,j,k,m}(t) \leq ubFleet_{i,j,m}(t) \Delta t + \sum_{z=0}^t \text{fleetInv}_{i,j,m}(z) \Delta z \quad (1g)
\]

Infrastructure upper bound for transportation flows

\[
\sum_{k} \sum_{m \in M_t} f_{i,j,k,m}(t) \leq ubInf_{i,j,t}(t) \Delta t + \sum_{z=0}^t \text{infInv}_{i,j,t}(z) \Delta z \quad (1h)
\]

\[
N^\text{sale}_{CV}(t), N^\text{sale}_{HEV}(t), N^\text{sale}_{PEV}(t), N^\text{sale}_{d}(t) = N^\text{sale}_{PEV}(t) P_d(d = d)
\]

\[
\text{CostFleetInv}^TP_{LV} = \sum_t (1 + r)^{-t} \sum_{LV} \text{vehCost}(t, LV) N^\text{sale}_{LV}(t), \quad \text{where} \ LV \in \{CV, HEV, d_1, d_2, \ldots, d_n\}
\]

\[
d_j^{ETP_{LV}}(t) = E(t) \sum_{LV} N^\text{cum}_{LV}(j, t), \quad \text{where} \ N^\text{cum}_{LV}(j, t) = N^\text{cum}_{LV}(j, t-1) - s_j N^\text{sale}_{LV}(t - T_{LV}) + s_j N^\text{sale}_{LV}(t)
\]

where:

\[
\text{CostOp}^E = \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costOp}_{i,j}^E(t) e_{i,j}(t) \quad (1i)
\]

\[
\text{CostInv}^E = \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costInv}_{i,j}^E(t) e_{i,j}(t) \quad (1j)
\]

\[
\text{CostOp}^T = \sum_t \sum_{(i,j,k,m)} (1 + r)^{-t} \text{costOp}_{i,j,k,m}^T(t) f_{i,j,k,m}(t) \quad (1k)
\]

\[
\text{CostFleetInv}^T = \sum_t \sum_{(i,j,m)} (1 + r)^{-t} \text{costFleetInv}_{i,j,m}(t) fleetInv_{i,j,m}(t) \quad (1l)
\]

\[
\text{CostFleetInv}^T = \sum_t \sum_{(i,j,l)} (1 + r)^{-t} \text{costFleetInv}_{i,j,l}(t) infInv_{i,j,l}(t) \quad (1m)
\]

Energy demand from the transportation system

\[
d_j^{ET}(t) = \sum_{(a,b) \in A^T_m} \sum_{m \in M_t} \text{fuelCons}_{a,b,m}(t) \sum_k f_{a,b,k,m}(t) + d_j^{ETP_{LV}}(t) \quad (1n)
\]

Decision variables:

Energy flows: \( e_{i,j}(t) \geq 0 \) \quad (1o)

Energy capacity inv.: \( lbe_{i,j}(t) \leq e_{i,j}(t) \leq ube_{i,j}(t) \) \quad (1p)

Transportation flows: \( f_{i,j,k,m}(t) \geq 0 \) \quad (1q)

Fleet inv.: \( ubFleet_{i,j,m}(t) \leq fleetInv_{i,j,m}(t) \leq ubFleet_{i,j,m}(t) \) \quad (1r)

Infrastructure inv.: \( ubInf_{i,j,m}(t) \leq infInv_{i,j,m}(t) \leq ubInf_{i,j,m}(t) \) \quad (1s)

Phase angles: \( -\pi \leq \theta_i(t) \leq \pi \) \quad (1t)
Model 0.1

\[ \text{min} \ \{ \text{CostOp}^E + \text{CostInv}^E + \text{CostOp}^T + \text{CostFleetInv}^T + \text{CostInfInv}^T \} \] (1a)

subject to:

1. Meet energy demand at every node
   \[ \sum_i \eta(i,j)(t) e(i,j)(t) - \sum_i e(j,i)(t) = d_j^E(t) + d_j^{ET}(t) \] (1b)

2. Energy flow lower and upper bounds
   \[ lbe(i,j)(t) \leq e(i,j)(t) \leq ube(i,j)(t) \Delta t + \sum_{z=0}^t eInv(i,j)(z) \Delta z \] (1c)

3. DC power flow equations
   \[ e(i,j)(t) = b(i,j) \left( \theta_i(t) - \theta_j(t) \right), \quad \forall (i,j) \in A^{EC}_C \] (1d)

4. Transportation demand for non-energy commodities
   \[ \sum_l f(i,j,k,m)(l) = d_{i,j,k}^T(l), \quad k \in \mathcal{K} \backslash \mathcal{K}_C \] (1e)

5. Transportation demand for energy commodities
   \[ \sum_m f(i,j,k,m)(m) = \text{heatContent}^E_k^{-1}(t) e(i,j,m)(k), \quad k \in \mathcal{K}_C \] (1f)

6. Fleet upper bound for transportation flows
   \[ \sum_k f(i,j,k,m)(k) \leq ubFleet(i,j,m)(t) \Delta t + \sum_{z=0}^t \text{FleetInv}(i,j,m)(z) \Delta z \] (1g)

7. Infrastructure upper bound for transportation flows
   \[ \sum_k f(i,j,k,m)(k) \leq ubInf(i,j,m)(t) \Delta t + \sum_{z=0}^t \text{InfInv}(i,j,m)(z) \Delta z \] (1h)

8. LDV sales
   \[ \sum_{LV} N_{\text{sale}}^{\text{LV}}(t) = N_{\text{sale}}(t), \quad \text{where} \ LV \in \{ \text{CV}, \ HEV, d_1, d_2, \ldots, d_n \} \]

where:

\[ \text{CostOp}^E = \sum_{(i,j)} \sum_t (1+r)^{-t} \text{costOp}^E_{i,j}(t) e(i,j)(t) \] (1i)

\[ \text{CostInv}^E = \sum_{(i,j)} \sum_t (1+r)^{-t} \text{costInv}^E_{i,j}(t) eInv(i,j)(t) \] (1j)

\[ \text{CostOp}^T = \sum_{(i,j,k,m)} \sum_t (1+r)^{-t} \text{costOp}^T_{i,j,k,m}(t) f(i,j,k,m)(t) \] (1k)

\[ \text{CostFleetInv}^T = \sum_{(i,j,m)} \sum_t (1+r)^{-t} \text{costFleetInv}^T_{i,j,m}(t) \text{FleetInv}(i,j,m)(t) \] (1l)

\[ \text{CostInfInv}^T = \sum_{(i,j,l)} \sum_t (1+r)^{-t} \text{costInfInv}^T_{i,j,l}(t) \text{InfInv}(i,j,l)(t) \] (1m)

Energy demand from the transportation system

\[ N_{\text{LV}}^{\text{cum}}(j,t) = N_{\text{LV}}^{\text{cum}}(j,t-1) - s_j N_{\text{LV}}^{\text{sale}}(t - T_{\text{LV}}) + s_j N_{\text{LV}}^{\text{sale}}(t) \] (1n)

\[ E^T_{j}(t) = \sum_{(a,b) \in A_T} \sum_{m \in M_{j}} \text{fuelCons}_{(a,b,m)}(t) f(a,b,k,m)(t) + \sum_{LV} E_{LV}(t) N_{\text{LV}}^{\text{cum}}(j,t) \]

Decision variables:

Energy flows:

\[ e(i,j)(t) \geq 0 \] (1o)

Energy capacity inv.:

\[ lbeInv(i,j)(t) \leq eInv(i,j)(t) \leq ubeInv(i,j)(t) \] (1p)

Transportation flows:

\[ f(i,j,k,m) \geq 0 \] (1q)

Fleet inv.:

\[ lbFleetInv(i,j,m)(t) \leq \text{FleetInv}(i,j,m)(t) \leq ubFleetInv(i,j,m)(t) \] (1r)

Infrastructure inv.:

\[ lbInfInv(i,j,l)(t) \leq \text{InfInv}(i,j,l)(t) \leq ubInfInv(i,j,l)(t) \] (1s)

Phase angles:

\[ \theta_i(t) \leq \pi \] (1t)

LDV sale:

\[ N_{\text{sale}}^{\text{LV}}(t) \geq 0, \quad \text{where} \ LV \in \{ \text{CV}, \ HEV, d_1, d_2, \ldots, d_n \} \]
min \{ \text{CostOp}^E + \text{CostInv}^E + \text{CostOp}^T + \text{CostFleetInv}^T + \text{CostInfInv}^T \} 

subject to:

Meet energy demand at every node
\[ \sum_j e(i,j(t)) - \sum_j e(i,j(t)) = d^E_j(t) + d^{ET}_j(t) \]  

Energy flow lower and upper bounds
\[ lbv(i,j)(t) \leq e(i,j)(t) \leq ubv(i,j)(t) \Delta t + \sum_{z=0}^t e(v,i,j)(z) \Delta z \]  

DC power flow equations
\[ e(i,j)(t) = b(i,j)(t - \theta_j(t)), \quad \forall(i,j) \in \mathcal{A}_{DC} \]  

Transportation demand for non-energy commodities
\[ \sum_m f(i,j,k,m)(t) = d^{TP}_{i,j,k}(t), \quad k \in \mathcal{K} \setminus \mathcal{K}_c \]  

Transportation demand for energy commodities
\[ \sum_m f(i,j,k,m)(t) = \text{HeatContent}^{TP}_{k}(t) e(n_{i,k},n_{j,k})(t), \quad k \in \mathcal{K}_c \]  

Fleet upper bound for transportation flows
\[ \sum_k f(i,j,k,m)(t) \leq ubFleet(i,j,m)(t) \Delta t + \sum_{z=0}^t \text{fleetInv}(i,j,m)(z) \Delta z \]  

Infrastructure upper bound for transportation flows
\[ \sum_k \sum_{m \in \mathcal{M}_t} f(i,j,k,m)(t) \leq ubInf(i,j,t)(t) \Delta t + \sum_{z=0}^t \text{infInv}(i,j,t)(z) \Delta z \]  

where:
\[ \text{CostOp}^E = \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costOp}^E_{i,j}(t) e(i,j)(t) \]  
\[ \text{CostInv}^E = \sum_t \sum_{(i,j)} (1 + r)^{-t} \text{costInv}_{i,j}(t) e(i,j)(t) \]  
\[ \text{CostOp}^T = \sum_t \sum_{(i,j,m)} (1 + r)^{-t} \text{costOp}_{i,j,m}(t) f(i,j,m)(t) \]  
\[ \text{CostFleetInv}^T = \sum_t \sum_{(i,j,m)} (1 + r)^{-t} \text{costFleetInv}_{i,j,m}(t) \text{fleetInv}_{i,j,m}(t) \]  
\[ + \text{CostFleetInv}^{TPLV} \]  
\[ \text{CostInfInv}^T = \sum_t \sum_{(i,j,t)} (1 + r)^{-t} \text{costInfInv}_{i,j,t}(t) \text{infInv}_{i,j,t}(t) \]  

Energy demand from the transportation system
\[ d^{ET}_j(t) = \sum_{(a,b) \in \mathcal{A}_{j}} \sum_{m \in \mathcal{M}_j} \text{fuelCons}_{i,j,m} \sum_{k \in \mathcal{K}} f(i,j,k,m)(t) + d^{ETPLV}_j(t) \]  

Decision variables:

Energy flows:
\[ e(i,j)(t) \geq 0 \]  

Energy capacity inv.: \[ lbv(i,j,t) \leq e(i,j,t) \leq ubv(i,j,t) \]  

Transportation flows:
\[ f(i,j,k,m) \geq 0 \]  

Fleet inv.: \[ lbFleet(i,j,m) \leq fleetInv(i,j,m) \leq ubFleet(i,j,m) \]  

Infrastructure inv.: \[ lbInf(i,j,t) \leq infInv(i,j,t) \leq ubInf(i,j,t) \]  

Phase angles:
\[ -\pi \leq \theta_i(t) \leq \pi \]
Model 1.0

It is assumed that for “most” vehicles in NHTS, the VMT happened on the assigned travel day “somehow” reflects their travel pattern on everyday basis.

\[
 f_{m,d}(u,v) = f_{d|m}(v|u)f_m(u) .
\]

\[
 f_d(x) = \int_0^\infty f_{m,d}(u,x) \, du = \int_0^\infty f_{d|m}(x|u)f_m(u) \, du .
\]
Model 1. $\frac{1}{2}$

\[
\begin{align*}
\min & \{ \text{CostOp}^E + \text{CostInv}^E + \text{CostOp}^T + \text{CostFleetInv}^T + \text{CostInfInv}^T \} \quad (1a) \\
\text{subject to:} & \\
\text{Meet energy demand at every node} & \sum_i \eta_{i,j}(t)e_{i,j}(t) - \sum_i e_{j,i}(t) = d^E_j(t) + d^{ET}_j(t) \\ 
\text{Energy flow lower and upper bounds} & lbe_{i,j}(t) \leq e_{i,j}(t) \leq ube_{i,j}(t) \Delta t + \sum_{z=0}^t e_{i,j}(z) \Delta z \\ 
\text{DC power flow equations} & e_{i,j}(t) = b_{i,j}\left(\theta_i(t) - \theta_j(t)\right), \quad \forall (i, j) \in \mathcal{A}_{DC}^E \\ 
\text{Transportation demand for non-energy commodities} & \sum_k f_{i,j,k,m}(t) = d^T_{i,j,k}(t), \quad k \in \mathcal{K} \setminus \mathcal{K}_c \\ 
\text{Transportation demand for energy commodities} & \sum_k f_{i,j,k,m}(t) = \text{heatContent}_{i,k}(t)e_{i,j}(t), \quad k \in \mathcal{K}_c \\ 
\text{Fleet upper bound for transportation flows} & \sum_k f_{i,j,k,m}(t) \leq ubFleet_{i,j,k,m}(t) \Delta t + \sum_{z=0}^t \text{fleetrInv}_{i,j,k,m}(z) \Delta z \\ 
\text{Infrastructure upper bound for transportation flows} & \sum_k f_{i,j,k,m}(t) \leq ubInf_{i,j,k,m}(t) \Delta t + \sum_{z=0}^t \text{infInv}_{i,j,k,m}(z) \Delta z \\ 
\text{LDV sales} & \sum_{LV} N_{\text{sale}}^{LV}(t) = N_{\text{sale}}(t), \text{where } LV \in \{\text{CV, HEV, PEV}\} \\
\end{align*}
\]

where:

\[
\begin{align*}
\text{CostOp}^E & = \sum_{t \in \mathcal{T}_{i,j}} (1 + r)^{-t} \text{costOp}_{E}^E(t) e_{i,j}(t) \\ 
\text{CostInv}^E & = \sum_{t \in \mathcal{T}_{i,j}} (1 + r)^{-t} \text{costInv}_{E}^E(t) e_{i,j}(t) \\ 
\text{CostOp}^T & = \sum_{t \in \mathcal{T}_{i,j,k,m}} (1 + r)^{-t} \text{costOp}_{T}^E(t) f_{i,j,k,m}(t) \\ 
\text{CostFleetInv}^T & = \sum_{t \in \mathcal{T}_{i,j,k,m}} (1 + r)^{-t} \text{costFleetInv}_{T}^E(t) f_{i,j,k,m}(t) + \sum_{t \in \mathcal{T}_{LV}} \text{vehCost}(t, LV) N_{\text{sale}}^{LV}(t) \\ 
\text{CostInfInv}^T & = \sum_{t \in \mathcal{T}_{i,j}} (1 + r)^{-t} \text{costInfInv}_{E}^E(t) \text{infInv}_{i,j}(t) \\
\end{align*}
\]

Energy demand from the transportation system

\[
\begin{align*}
N_{\text{LV}}^{\text{cum}}(j, t) & = N_{\text{LV}}^{\text{cum}}(j, t-1) - s_j N_{\text{LV}}^{\text{sale}}(t - T_{\text{LV}}) + s_j N_{\text{LV}}^{\text{sale}}(t) \\ 
\text{fleetrInv}_{i,j}(t) & = \sum_{(a,b) \in \mathcal{A}_{T}} \sum_{m \in \mathcal{M}_j} \text{fuelCons}_{(a,b,m)}(t) \sum_{k \in \mathcal{K}} f_{a,b,k,m}(t) + \sum_{LV} E_{\text{LV}}(t) N_{\text{LV}}^{\text{cum}}(j, t) \\
\end{align*}
\]

Decision variables:

Energy flows: $e_{i,j}(t) \geq 0$ (10)

Energy capacity inv.: $lbe_{i,j}(t) \leq e_{i,j}(t) \leq ube_{i,j}(t)$ (1p)

Transportation flows: $f_{i,j,k,m}(t) \geq 0$ (1q)

Fleet inv.: $lbFleet_{i,j,k,m}(t) \leq flFleet_{i,j,k,m}(t) \leq ubFleet_{i,j,k,m}(t)$ (1r)

Infrastructure inv.: $lbInf_{i,j}(t) \leq inf_{i,j}(t) \leq ubInf_{i,j}(t)$ (1s)

Phase angles: $-\pi \leq \theta_i(t) \leq \pi$ (1t)

LDV sale: $N_{\text{sale}}^{\text{sale}}(t) \geq 0$, where $LV \in \{\text{CV, HEV, PEV}\}$
Discussion

- Forecast total light-duty vehicle sale vs. life time
- Light-duty PEV travel pattern is the same as LDV
- LDV travel pattern will not be affected by decisions of other passenger transportation mode, e.g., airplane, train, etc.
- Distribution of new LDV among states