Holistic Modeling of Future Transportation Energy Use and Emissions: Transportation Energy and Mobility Pathway Options (TEMPO) Model

PI: Paige Jadun (presenter)

Project Team: Catherine Ledna, Arthur Yip, Chris Hoehne, Jiayun Sun, Dan Mazzone, Abby Wheelis, Bo Liu, Sailesh Acharya, Brennan Borlaug

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VAN050

Project Overview

Timeline

- **Project start date**: 11/14/2022
- **Project end date**: 12/31/2025
- **Percent complete**: 80%

Budget

- **Total project funding**: $1,500,000
    - **U.S. Department of Energy (DOE) share**: 100%
- **Funding for FY 2024**: $500,000
- **Funding for FY 2025**: $500,000

Barriers

This work aims to develop robust and agile **modeling capabilities** to explore **"Uncertainty about the future of mobility [which] complicates forward-looking technology evaluation and R&D prioritization"** (Vehicle-Mobility Systems Analysis 2023 Technical Team Roadmap)

- What does the **future of mobility** look like?
- What are the **ranges of possible scenarios** for how people and goods will move in the future?
- What would be the **vehicle fleet composition**?
- How will changes impact **future R&D portfolios**?

Partners

(TEMPO Steering Committee)

- California Air Resources Board
- Electric Power Research Institute
- ExxonMobil
- Ford
- ClimateWorks
- Boston University
- Stanford University
- University of California, Davis
- U.S. Energy Information Administration (EIA)
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory
- U.S. Environmental Protection Agency
- U.S. Department of Transportation

Project Relevance

Motivation

- The transportation sector is on the verge of a radical transformation, driven by **rapidly evolving technologies, consumer preferences, and policies.**
- Continuous **development and maintenance of analytical models** are required to answer evolving research questions.

Objectives

- Maintain and continue development of the National Renewable Energy Laboratory's (NREL's) **TEMPO™ model** to enable new and relevant **transportation energy use analyses**, reflective of current technological and policy landscapes.
- Support DOE in answering high-urgency, quick-turnaround analysis requests to support decision-making.

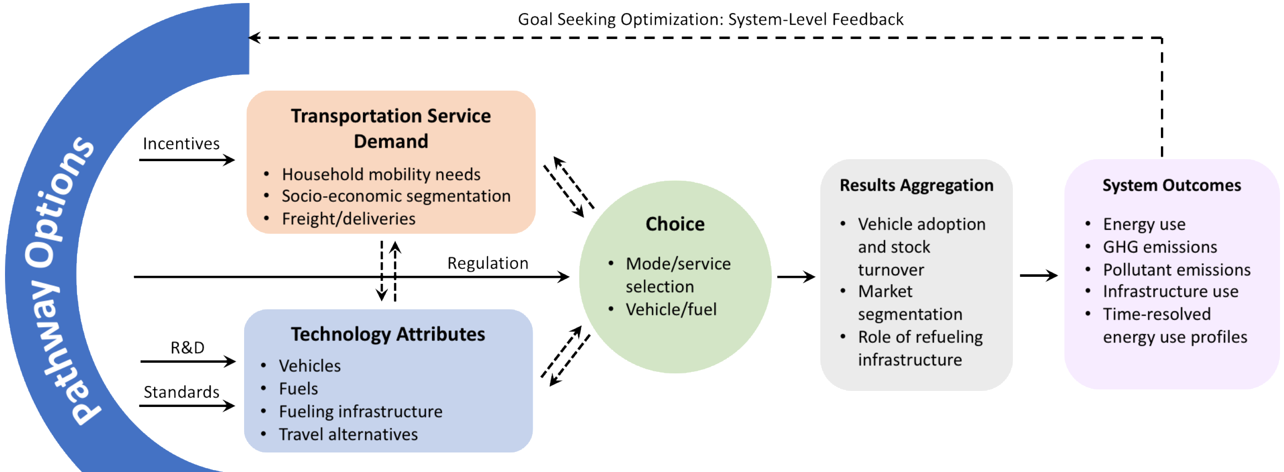
Impact

- Advancement of modeling and analysis state-of-the-art to answer timely questions with an increased degree of **confidence, fidelity, and transparency** covering all modes of passenger and freight travel in the United States.
- Improved ability for DOE and other stakeholders to **gain insights into the future evolution of transportation energy use** and analyze the potential adoption of alternative vehicle technologies and transportation solutions in a way that is **affordable** and **synergistic with the broader energy system**.

Project Approach

TEMPO

TEMPO is a comprehensive transportation demand model designed to explore long-term scenarios of energy use across all modes of transportation with representation of various technology options



Summary of TEMPO modeling approach, Muratori et al. 2020

Project work revolves around TEMPO and is divided into **three primary workstreams:**

Capability Development and Model Enhancement

- Consult with VTO, steering committee to prioritize development
- Document enhancement-related insights
- Support ongoing and upcoming analysis

Model Upkeep

- Train new staff
- Document model
- Update data sources
- Maintain model (code versioning, bug fixes, etc.)

Quick Turnaround Analysis

- Respond to VTO quick-turnaround strategic requests
- Quickly run scenarios with alternative input assumptions to produce key metrics, visualizations

Project Approach: Why TEMPO?

TEMPO is a key tool in the DOE arsenal to explore future transportation energy use and emissions scenarios across the entire sector.

Examples of recent TEMPO applications:

"Assessing Cost Competitiveness of Zero-Emission Trucks," published in *iScience*. Ledna et al. 2024 → Estimates to inform cost-competitiveness and **potential cost savings of various technology options** across use cases

"Exploring Decarbonization Pathways for USA Passenger and Freight Mobility," published in *Nature Communications*. Hoehne et al. 2023 → Insights on **uncertainty in future transportation system** evolution and impacts on fuel demand, energy use, etc.

Highly Resolved Projections of Passenger Electric Vehicle Charging Loads for the Contiguous United States, NREL report. Yip et al. 2023

Electric Vehicle Managed Charging: Forward-Looking Estimates of Bulk Power System Value, NREL report. Hale et al. 2023

→ Scenarios of hourly and county-level electric vehicle **(EV) load profiles** and related **grid analysis** to inform effective and affordable EV-grid integration

TEMPO also supports and/or coordinates with multiple DOE projects, including VAN023, VAN054, VAN055, VAN061, EEMS128, and EERE's Integrated Energy Futures program.

Milestones

Milestone	**Date**
Draft publication of complete **model documentation** and accompanying data set of TEMPO results for a baseline and one or more alternative scenarios to be made publicly available	**FY24 Q3 (complete)**
Summary of model upkeep activities, updates, and estimated impacts on results for FY 2024	**FY24 Q4 (complete)**
Annual publication of model enhancement(s): Publication (draft paper) of at least one model enhancement and related results and insights for FY 2025	**FY25 Q1 (complete)**
Model enhancement on transportation affordability: Implementation and related analysis on at least one model enhancement focused on improved representation of transportation costs and affordability	FY25 Q3 (in progress)
Summary of TEMPO model upkeep activities, updates, and estimated impacts on results for FY 2025	FY25 Q4

In addition, the project team holds **regular check-in presentations with DOE-VTO** summarizing TEMPO model and data updates and impacts on results and reviewing quick-turnaround analyses, prioritization of model enhancements, and the needs and timeline for publication of analysis insights and/or data sets.

Technical Accomplishment: Updated light-duty vehicle (LDV) technology adoption calibration

Technology adoption formulation and calibration updated to reflect key parameters in consumer decision-making, utilizing a variety of data inputs:

- County-level vehicle sales and make/model availability (Experian)
- State-level fuel prices and vehicle tax credits (EIA, Alternative Fuels Data Center [AFDC])
- Vehicle cost and efficiency (Autonomie vehicle modeling in Islam et al. 2023)
- Travel data and infrastructure enabled trip feasibility (National Household Travel Survey, AFDC, National Highway System, Ge et al. 2021)

Formulation of utility of adopting a vehicle of technology, *t*

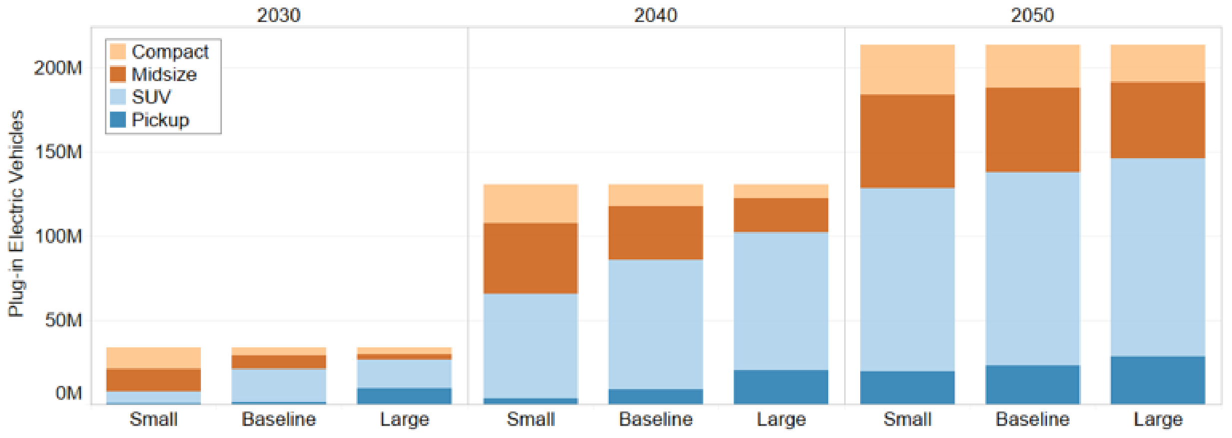
$$u_t = \alpha_t + K_1\left(\underbrace{C_t^{total}}_{\text{Vehicle and fuel cost}} + \underbrace{T_t^{charge}V^{time}}_{\text{Charging time cost (time x value of time)}}\right) + K_2\underbrace{F_t^{com}}_{\text{Community trip feasibility}}\underbrace{W^{com}}_{\text{Community trip weight}} + K_3\underbrace{F_t^{cor}}_{\text{Corridor trip feasibility}}\underbrace{W^{cor}}_{\text{Corridor trip weight}} + K_4\log\underbrace{M_t}_{\text{Make/model availability}}$$

Parameterizing factors of adoption can provide insights on potential consumer response to market changes and greater transparency of model results

Technical Accomplishment: Updated analysis of heterogenous LDV EV adoption

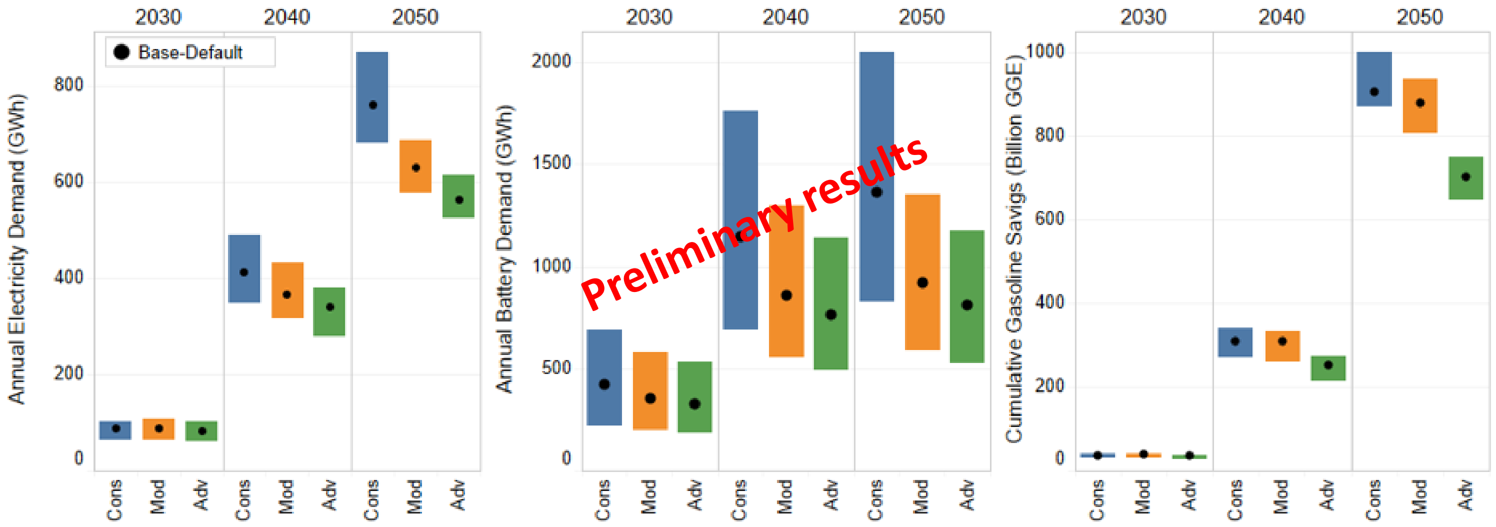
Objective: How does **heterogeneous adoption by vehicle class and/or vehicle range** impact energy use, emissions, charging needs, and/or vehicle manufacturing requirements?

Approach: For a specific scenario with **exogenous LDV technology shares** (current results based on Muratori et al. [forthcoming]), assess impacts of adoption **varying which vehicles electrify first** and associated vehicle **range** and **efficiency**.



What vehicles are electrified/displaced matters: Across *preliminary* bounding scenarios with "Mid" technology assumptions, difference in 2030 of:

- 38 TWh electricity demand (58%)
- 382 GWh battery demand (290%)
- 9.7 billion GGE gasoline savings (32%)



Additional results provided in technical backup slides.

Technical Accomplishment: Developed preliminary on-road vehicle technology adoption scenarios to reflect current data and policy

A range of preliminary technology adoption scenarios were developed for on-road light-duty and medium- and heavy-duty vehicles based on updates to key assumptions for:

- **Vehicle and fuel attributes:** Cost and performance updated to scenario values in 2024 Transportation Annual Technology Baseline (ATB), building upon Argonne National Laboratory (ANL) Autonomie modeling
- **Charging infrastructure:** Availability assumptions developed at varying levels (low, mid, high) for residential and public charging
- **Policy:** Incorporated representations of relevant FY 2024 policies and impacts on vehicle technologies (policy implementations can be turned on/off)
- **Technology adoption calibration:** Technology adoption parameters recalibrated to reflect updated vehicle and fuel assumptions
- **Biofuels:** Workflow developed to incorporate biofuel production impacts from NREL’s Bioenergy Scenario Model to inform biofuel blend rates and carbon intensity (in progress).

Scenarios provide range of potential transportation futures and quantify directional influence of technology costs, infrastructure, etc. on the role of various technology options – insights can help inform planning and/or R&D direction

Technical Accomplishment: Completed various model maintenance tasks to improve model transparency and efficiency

- Completed draft report of **updated model documentation**
- **Optimized workflow to enable scenario batching** and automated report generation, enabling large scenario suites on high-performance computer
- Added tracking and output **reporting of vehicle adoption attributes** to assess influence of input parameters and changes across scenarios
- Formalized **ATB to TEMPO workflow** to develop vehicle cost inputs, reducing turnaround time for product updates
- Implemented **tracking of dollar year and heating value** assumptions across all model inputs to ensure consistency across inputs from various data sources

Model updates are intended to:

- **Improve transparency** of model assumptions and influence of input variables
- **Increase efficiency** of developing data inputs and scenarios, and running the model
- **Enforce consistency** of data values across inputs.

Collaboration and Coordination With Other Institutions

- The **TEMPO steering committee** (SC) was established in 2019 to guide model development and identify top priority research questions that TEMPO should address.
  - Participation consists of members from **government organizations, industry, research institutions, and academia,** including:
    - DOE Bioenergy Technologies Office
    - DOE Hydrogen and Fuel Cell Technologies Office
    - DOE Strategic Analysis
    - U.S. Energy Information Administration
    - U.S. Department of Transportation
    - California Air Resources Board
    - Electric Power Research Institute
    - ClimateWorks
    - ExxonMobil
    - Ford
    - Boston University
    - Stanford University
    - University of California, Davis
    - Oak Ridge National Laboratory
    - Pacific Northwest National Laboratory.

In **FY 2024**, project team briefed the SC on representation of relevant policies and ongoing projects (VAN055, EEMS128); the team plans to engage the SC in **FY 2025** to discuss technology adoption scenario results and general model updates.

- The project team also regularly coordinates with **Argonne National Laboratory** (ANL) on vehicle cost modeling results from Autonomie (key TEMPO input), and **Oak Ridge National Laboratory** (ORNL) for representation of used vehicle markets and vehicle survival.

Responses to Previous Reviewer Comments

Coupling with supply side models: For impacts of legislation and supply side changes, the reviewer suggested the team identify models or suites of models it thinks will assist with this.

- Through this and other TEMPO work, the team has:
  - Developed a workflow to incorporate biofuel production results from **NREL's Bioenergy Scenario Model** and discussed potential integration options with **ORNL's BioTrans model**
  - Initiated a project to integrate with **NREL's ReEDS-FINITO** model (power sector + industry models) to inform electricity/fuel prices
  - Coordinated with **ANL's POLARIS** model to extrapolate insights from city-scale, agent-based modeling to TEMPO's county-level representation (e.g., impact of land-use changes, transit-oriented development) (EEMS128).

Documentation and collaboration: Reviewer suggested continuing to improve documentation and expand collaboration with stakeholders will be important going forward, particularly on the demand-related factors and communication of scenarios.

- The team will continue to engage with the steering committee to discuss new TEMPO results and has been in coordination with the U.S. Drive Vehicle-Mobility Systems Analysis Tech Team on scenario development for related TEMPO projects.

Web-based TEMPO: Reviewer believed that a version of "TEMPO-light" would be very useful to practitioners who do not have access to other trusted, national transportation energy use models.

- A public-facing scenario explorer (e.g., similar to EVI-Pro Lite) is out of scope for the current project but is a key capability for proposed future work.

Any proposed future work is subject to change based on funding levels.

Remaining Challenges and Barriers

- **Rapidly changing transportation landscape** increases uncertainty in future scenarios; analyses may require **greater range of model assumptions** and development of **appropriate scenario narratives** to feed into ongoing analyses.

- TEMPO scenarios should include impacts on **transportation affordability** in addition to impacts on energy use and emissions.

- Growth in modeling team and rate of model enhancements (across TEMPO projects) necessitates implementation of **software development and documentation best practices.**

Proposed Future Research

FY 2025

- Hold steering committee meeting on updated TEMPO scenario results and recent model development
- Support finalization of technology adoption scenario results for use in other ongoing projects, which reflect range of policy and technology assumptions
- Add capability to estimate LDV ownership costs by income category (Q3 Milestone)
- Publish TEMPO model documentation as NREL report
- Initiate unit testing to improve code quality and add validation to automated reporting comparing results to historical and baseline values (e.g., comparison to Annual Energy Outlook).

Future

- Develop public-facing TEMPO-Lite for easy exploration of alternative scenarios and potential integration with existing tools (e.g., EVI-Pro Lite)
- Refine representation of non-road modes with related analysis
- Update TEMPO documentation to web-based platform to better support continuous updates and potential integration with source code
- Expand model transparency by exploring and implementing methods to reflect uncertainty in model outputs (i.e., assign confidence intervals and/or uncertainty bands to results).

In addition, continue to respond to quick-turnaround strategic requests from VTO/DOE as they arise

Any proposed future work is subject to change based on funding levels.

Summary

The **transportation and energy landscapes are rapidly changing**, requiring the continuous development of tools to tackle evolving research questions.

Enhancement, maintenance, and application of the TEMPO model **enable and directly support larger VTO programmatic goals** to understand and support adoption of efficient and **sustainable transportation technologies and solutions** in a way that is **synergistic** with the broader energy system.

Key Project Takeaways

- **Key FY24-FY25 activities** include:
  - Incorporated representations of relevant FY 2024 policies
  - Refined and recalibration LDV technology adoption formulation, and increased transparency of adoption output results
  - Implemented a variety of model enhancements to improve model efficiency, consistency, and transparency.
- **Remaining key FY25 activities** include:
  - Support finalization of on-road vehicle adoption scenarios required for ongoing analyses
  - Include affordability estimates in TEMPO results
  - Publish TEMPO documentation.
- Model enhancements **support opportunities for new and ongoing** analysis in DOE portfolio.
- Recent and ongoing analyses **couple TEMPO to other tools** to expand scope of research questions.
- Engagement with **diverse steering committee** will inform modeling and analysis priorities.
- Project structure is intended to **flexibly respond to critical analysis needs** as they arise.
- Project is **on track**.

Thank You

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Paige.Jadun@nrel.gov

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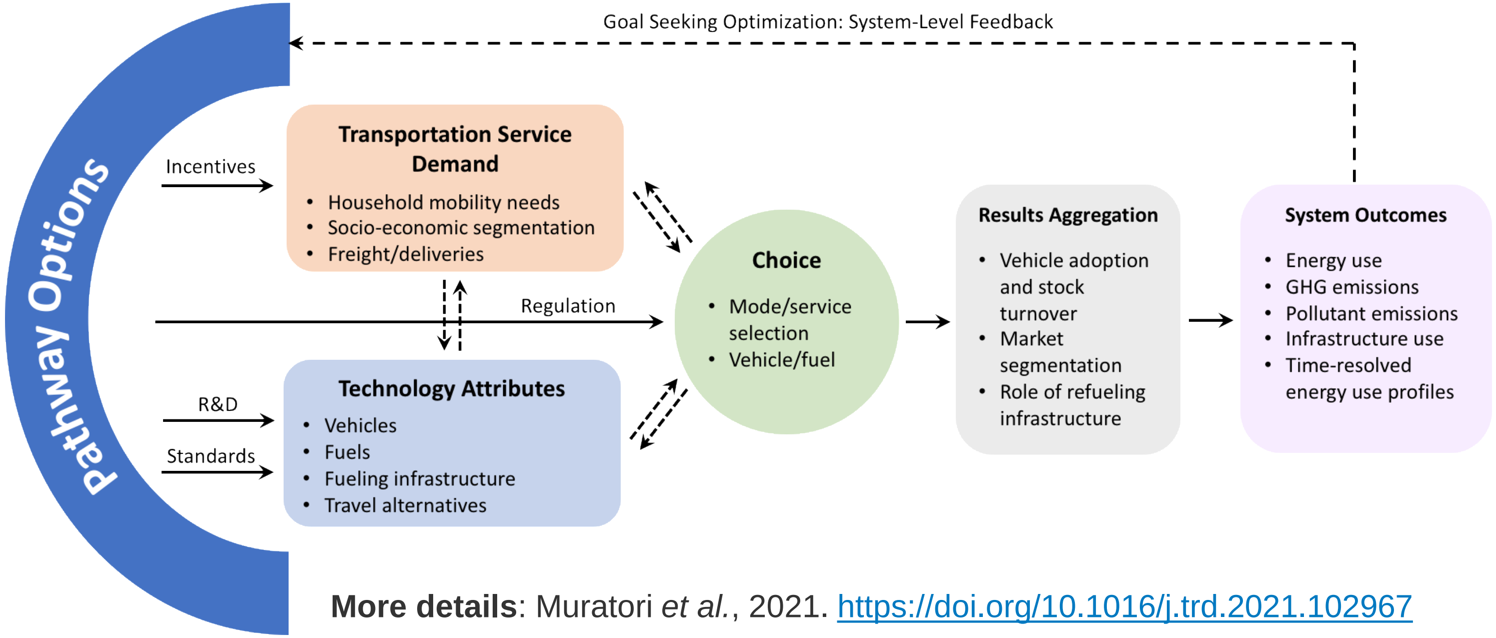
Technical Backup Slides

What is TEMPO?

The Transportation Energy & Mobility Pathway Options (TEMPO™) model is a **comprehensive transportation demand macro model to explore long-term scenarios** of energy use across all transportation segments and to integrate with large, multisectoral studies.



More details: Muratori *et al.*, 2021. https://doi.org/10.1016/j.trd.2021.102967

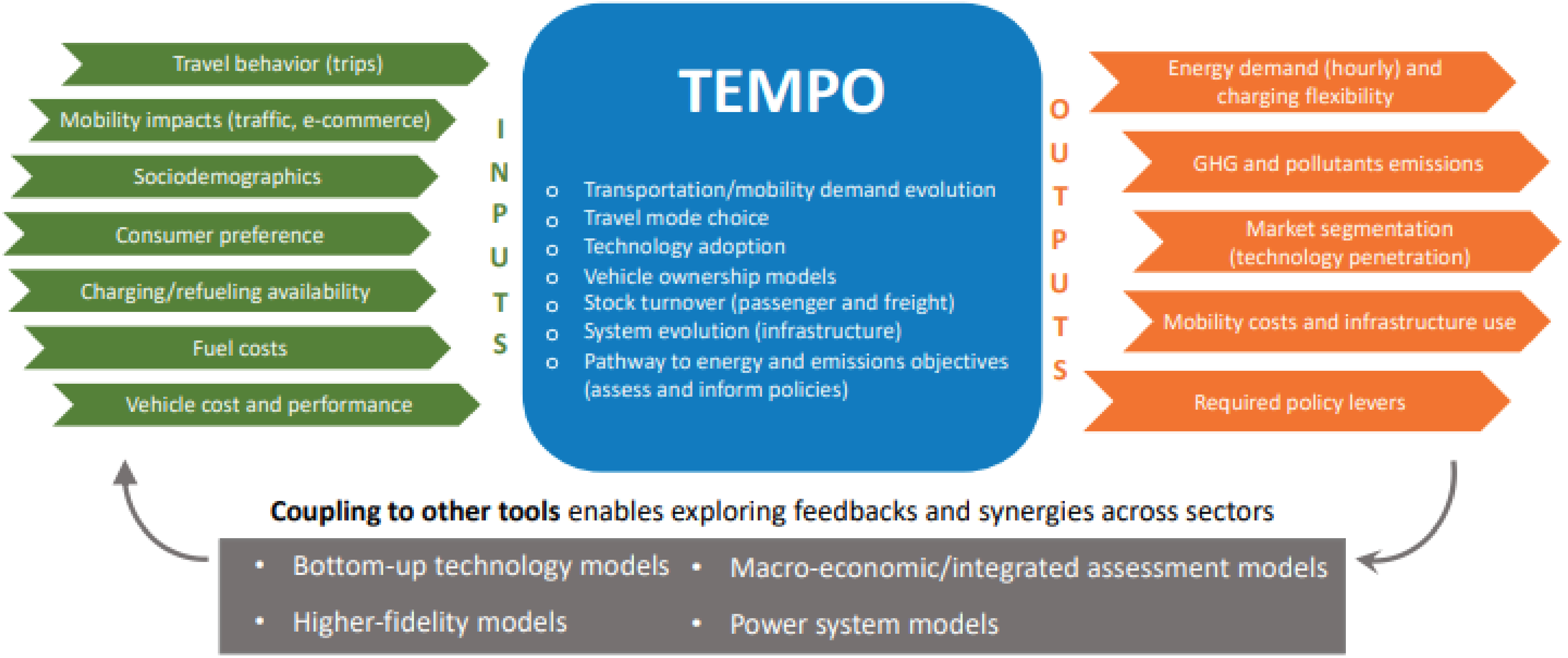
TEMPO models domestic passenger and freight travel demand across all travel modes and projects their evolution over time to answer questions such as:

- What is the potential for radical transformations of transportation supply and demand?
- How might interconnections with other sectors and infrastructure evolve?
- Which fuels/technologies will be adopted and in which market segments?

Modeling framework enables coupling with other tools to inform inputs and assess the broader impacts of TEMPO results

Alternative scenarios can be run by varying inputs on technology, consumer behavior, system attributes, etc.—where inputs can be informed by other models

TEMPO generates **internally consistent outputs to estimate impacts** on technology adoption, energy use, emissions, etc., which can further inform additional analyses

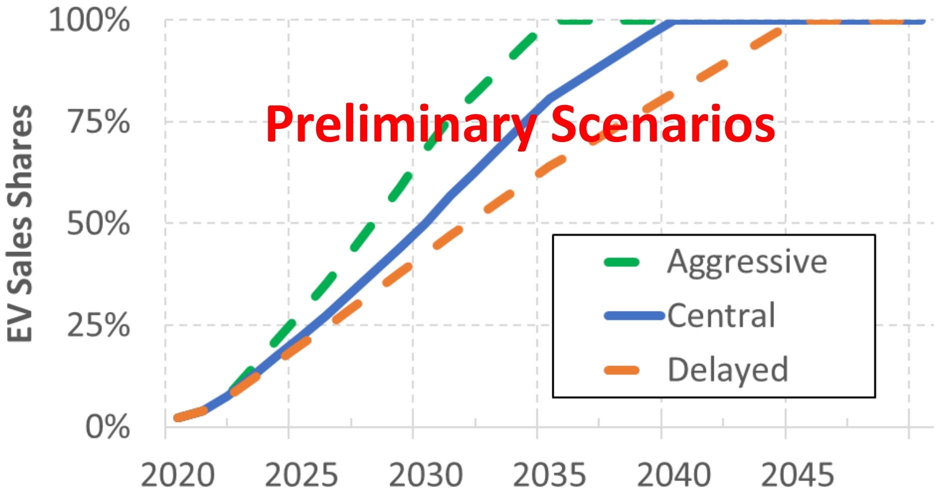


https://www.nrel.gov/transportation/tempo-model.html

LDV Analysis: Model Approach

- **Objective:** How does **heterogeneous adoption by vehicle class and/or vehicle range** impact energy use, emissions, charging needs, and/or vehicle manufacturing requirements?
- **Approach:** For a specific scenario with exogenous LDV technology shares (based on Muratori et al. [forthcoming]), assess impacts of adoption **varying which vehicles electrify first** and associated vehicle **range and efficiency**.

Using "Central" adoption case from Muratori et al. (forthcoming)

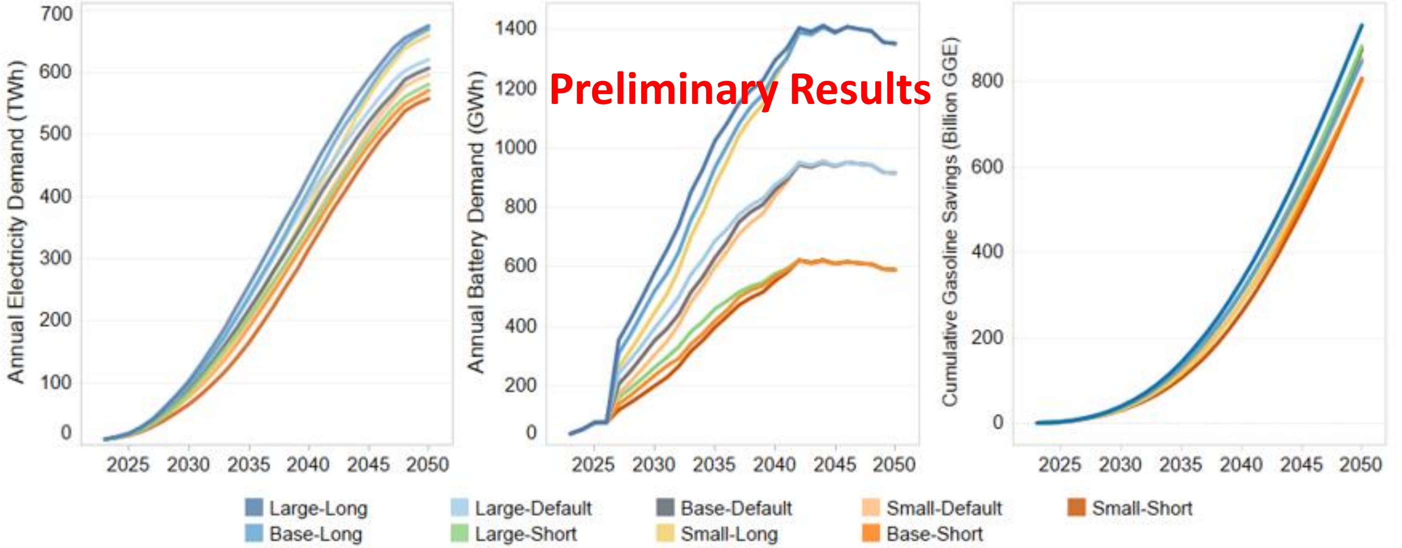


Dimension	Setting	Description
Allocation of EVs by Size Class	*Baseline (Base)*	Future EV sales are estimated based on TEMPO's endogenous formulation of vehicle technology utility and technology adoption.
	Small	Future EV sales are first allocated to the smallest (compact) vehicles, then further allocated based on ascending size class (midsize, SUV, pickup).
	Large	Future EV sales are first allocated to the largest (pickup) vehicles, then further allocated based on descending size class (SUV, midsize, compact).
Range Preference	*Default*	Ranges of future EV sales follow the same assumption as Muratori et al. (forthcoming): 300-mile range for battery-electric vehicles (BEVs) and 50-mile range for plug-in hybrid electric vehicles (PHEVs).
	Short	Ranges of future EV sales are assumed to be 200 miles for BEVs and 25 miles for PHEVs.
	Long	Ranges of future EV sales are assumed to be 400 miles for BEVs and 50 miles for PHEVs.
Technology Advancement	*Moderate (Mod)*	Vehicle technology progress follows the Moderate trajectory from the 2024 Transportation Annual Technology Baseline (ATB) (NREL 2024).
	Conservative (Cons)	Vehicle technology progress follows the Conservative trajectory from the 2024 Transportation ATB (NREL 2024).
	Advanced (Adv)	Vehicle technology progress follows the Advanced trajectory from the 2024 Transportation ATB (NREL 2024).

LDV Analysis: Energy and Battery Demand Results

- Across bounding scenarios (Large-Long vs. Small-Short) for the **Mid technology** case, difference in **2030** of:
  - 38 TWh electricity demand (58%)
  - 382 GWh battery demand (290%)
  - 9.7 billion GGE gasoline savings (32%).
- In **2050 Mid technology** case:
  - 117 TWh electricity demand (21%)
  - 762 GWh battery demand (229%)
  - 129 billion GGE gasoline savings (16%).
- Relative difference across scenarios decreases over time as stock converges; impact of vehicle range increases over time compared to vehicle class.
- What vehicles are electrified/displaced matters! (Example: Regulations without class specificity may lead to varying outcomes and/or growing demand for larger/longer-range vehicles = higher supply side demands.)
- Analysis assumes vehicle demand by class consistent with EIA Annual Energy Outlook; scenarios with increased SUV/pickup demand would lead to higher changes.

Absolute Electricity Demand, Battery Demand, and Cumulative Gasoline Savings



Difference From Baseline-Default