NREL
Transforming ENERGY

TEMPO

*The Transportation Energy and Mobility Pathway Options (**TEMPO**) Model*

Overview and Validation of V1.0

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

Core TEMPO Team

Matteo Muratori, PhD

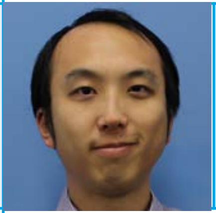
- Long-term transformation scenarios
- Integrated transportation-energy systems analysis

Paige Jadun

- Integrated energy system analysis
- Vehicle electrification and grid integration

Brian Bush, PhD

- Advanced modeling techniques
- Code development and implementation



Arthur Yip, PhD

- Vehicle choice and policy/regulatory compliance
- Regionalization (county-level) analysis

Chris Hoehne, PhD

- Passenger mode choice
- Data processing and model validation

Catherine Ledna

- Integrated assessment analysis
- Code and data processing

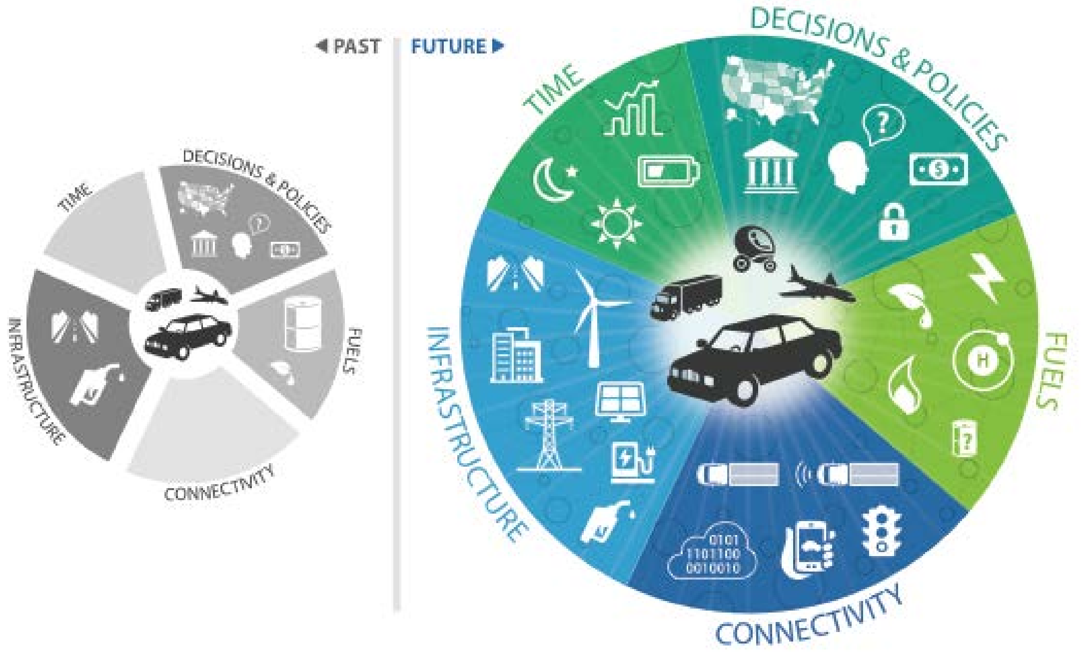
- Other TEMPO contributors include Laura Vimmerstedt, Jeff Gonder, Chris Gearhart, Doug Arent
- Extensive **steering committee** of international experts

INTRODUCTION

What is TEMPO and why we developed it?

After over a century of petroleum dominance, the transportation sector is **on the verge of radical transformations** driven by rapid technology advancements, automation, new mobility options and business models, and policies at all levels of government.

Migrating from a petroleum-based system to alternative fuels will introduce profound changes in technology adoption and create unprecedented integration opportunities.

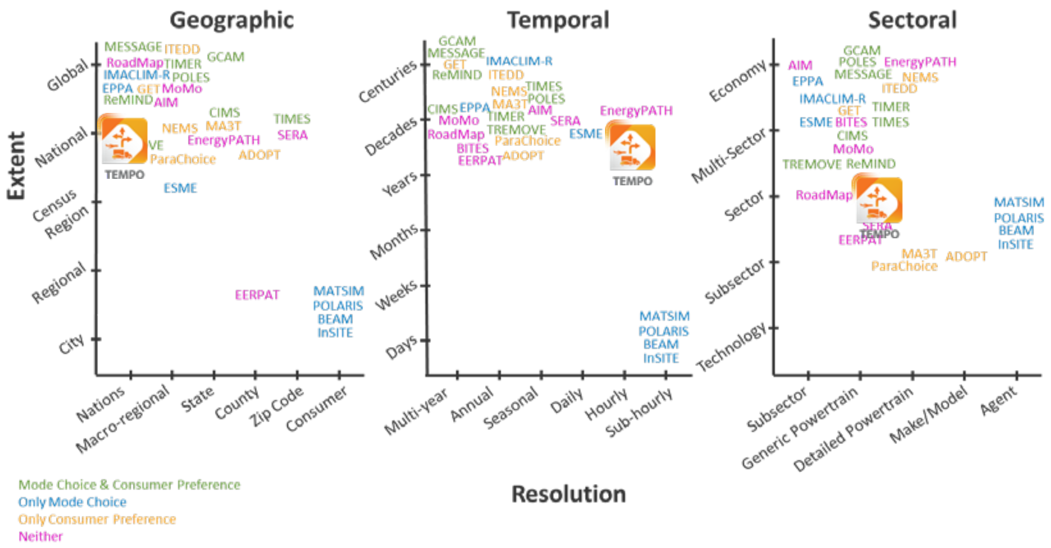


Why Developing a New Model? (Lit Review)

TEMPO

A new generation of integrated mobility-energy systems models is needed to capture emerging trends and explore future mobility technologies and systems:

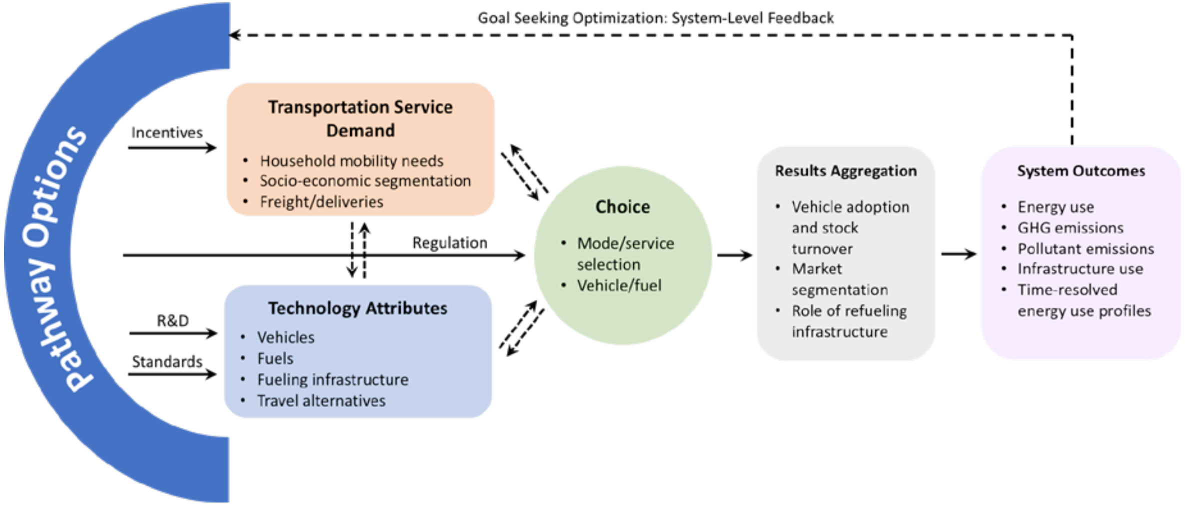
- **Emerging trends** – New ownership/ business models, electrification, alternative fuels, automation
- **Multi-sectoral dynamics** – supply-demand integration, especially grid
- **Spatiotemporal resolution**
- **Locus of choice** – heterogeneities of people, markets, and places and their influence on decisions and technology adoption.



Muratori et al., "[Future integrated mobility-energy systems: A modeling perspective](#)." Renewable and Sustainable Energy Reviews 119 (2020).

What is TEMPO?

The TEMPO model is a **comprehensive transportation demand macro model to explore long-term scenarios of energy use across all transportation modes** and to integrate with large multi-sectoral studies.



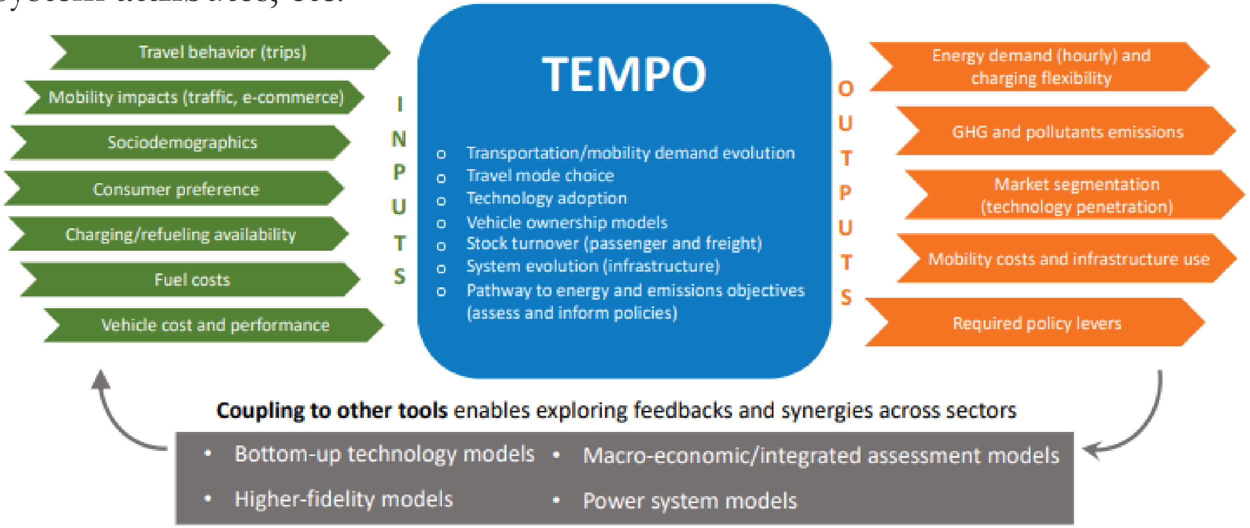
TEMPO fills a research gap on sector-wide transportation modeling, answering questions like:

- 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?

TEMPO finds pathways to achieve energy/emissions goals and estimate implications of different scenarios or decisions

Alternative **scenarios** can be run by varying inputs on technology cost and performance, consumer behavior, system attributes, etc.

TEMPO generates **internally consistent outputs to estimate impacts** on travel demand, technology adoption, energy use, emissions, etc.



The framework envisions **coupling with other tools** to inform inputs and assess the broader impacts of TEMPO results.

TEMPO Key Modeling Features

TEMPO

The TEMPO model incorporates and integrates the capabilities of several bottom-up, technology-rich models within an **integrated framework** to capture:

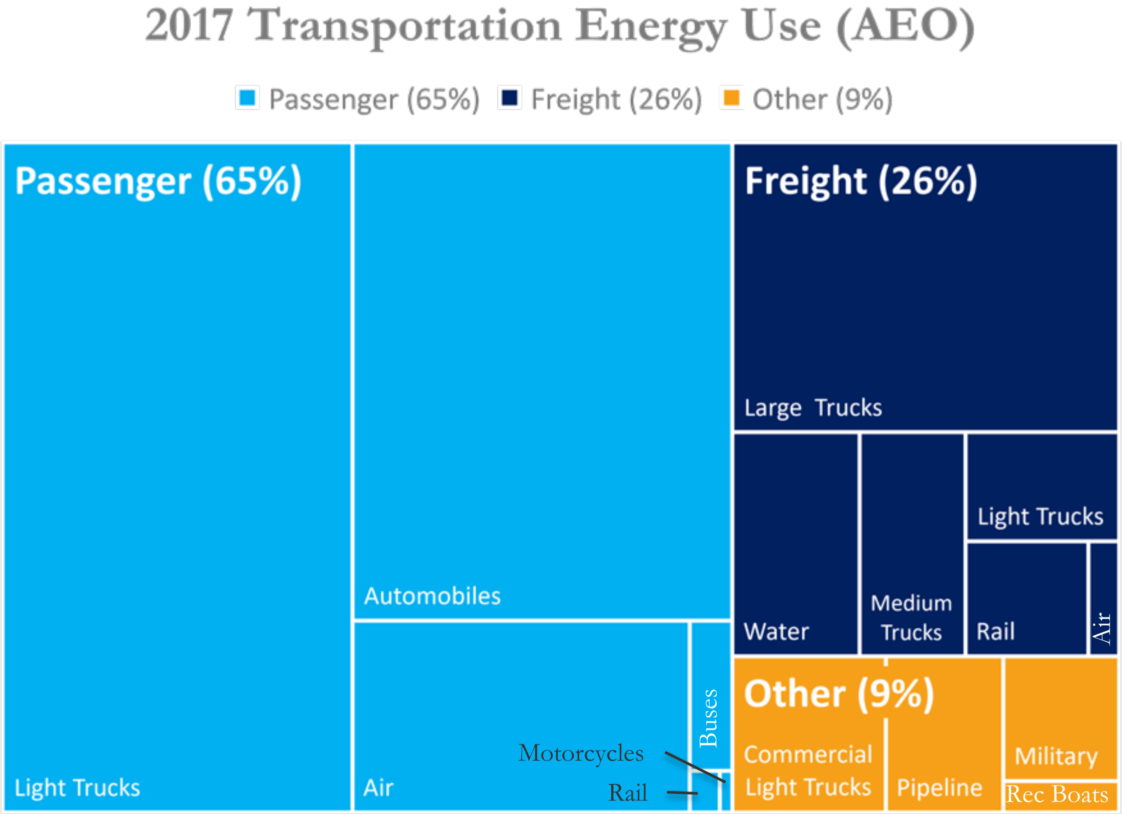
- **Heterogeneity of decision-makers:** innovative **household-level** activity-based travel demand, vehicle ownership, and mode/tech choice based on technology attributes and consumer preferences
- Impacts of supply and demand integration, which depend on **time-resolved energy use** based on individual trips (hourly-level), and the **role of refueling infrastructure** in supporting and enabling use of alternative fuels
- **Endogenous out-of-sample forecasting** to extrapolate recent emerging trends and capture impacts of technology breakthrough and socio-economics changes
- Non-linear trends, dynamics, and **complex feedbacks** reinforcing or enabling technology adoption (*e.g.*, PEV-CAV nexus, charging flexibility for grid support, latency-driven system-level decisions)
- Simple and fast execution to explore exogenous disruption and **explore "what-if?" scenarios.**

MODEL OVERVIEW

What TEMPO does, and how.

Scope: Passenger and Freight Mobility

TEMPO



~15% of AEO transportation energy use is not related to passenger/freight mobility, and it is **not currently modeled endogenously in TEMPO:**

- 8.9% – Other
- 4.3% – Commercial vocational vehicles
- 1.8% – Government and utility light-duty fleets.

TEMPO can track energy use, technology choices, and emissions for these modes (and others, like off-road vehicles that are not included in AEO transportation).

Coverage and Resolution

TEMPO

The TEMPO model is intended to study **future transportation systems and their interactions with infrastructure and energy supply** to answer novel and emerging questions.

✓ **Extent/coverage**:

- Entire transportation sector (including passenger and freight)
- National scale (implicit geography representation)
- Long-term assessments (*e.g.*, 2050)
- Existing and anticipated mode/technologies.

✓ **Resolution**:

- Scalable regional resolution
- Hourly energy demand.

High geographic resolution available through county-specific data inputs (e.g., household demographics, fuel cost, infrastructure availability, etc.)

Passenger/Freight Travel Demand Binning

TEMPO

Passenger and freight demand is binned in TEMPO based on socio-demographics, geography, time, and shipment characteristics to represent the **heterogeneity of demand and choice** along these dimensions.

The representation of time bins allows for estimation of time-resolved energy use profiles.

Household Bin Dimensions		
Household Composition	**Income**	**Urban Classification**
- No drivers - Single driver - Multiple drivers small - Multiple drivers large Small = 2 people or less Large = more than 2 people	- Low (<$50k) - Middle ($50k - $125k) - High ($125k+)	- Urban - Suburban - Secondary city - Small town - Rural

Time Bin Dimensions	
Weekday	**Time Period**
- Weekday - Weekend	- 1: From 00:00 to 01:59 - 2: From 02:00 to 03:59 - 3: From 04:00 to 05:59 - 4: From 06:00 to 07:59 - 5: From 08:00 to 09:59 - 6: From 10:00 to 11:59 - 7: From 12:00 to 13:59 - 8: From 14:00 to 15:59 - 9: From 16:00 to 17:59 - 10: From 18:00 to 19:59 - 11: From 20:00 to 21:59 - 12: From 22:00 to 23:59

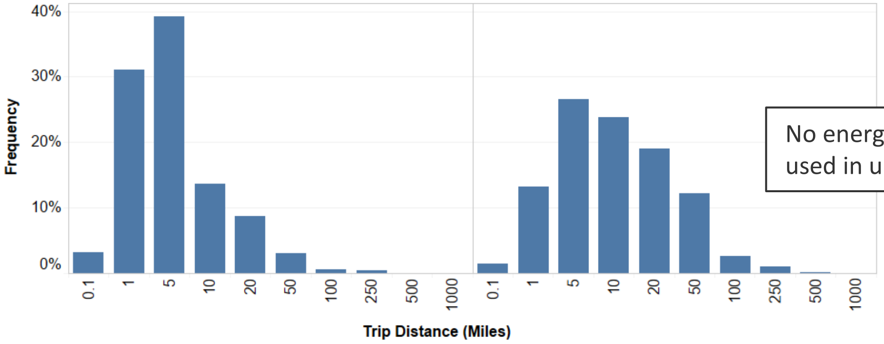
Freight Bin Dimensions		
Distance	**Time Sensitivity**	**Operating Period**
- 0 to 99 Miles - 100 to 249 Miles - 250 to 499 Miles - 500 to 749 Miles - 750 to 999 Miles - 1000 to 1499 Miles - 1500 to 1999 Miles - Over 2000 Miles	- Time Sensitive - Time Insensitive	- Diurnal - Nocturnal - Continuous

Binning is implemented to **represent differences in travel demand and travel choice** by sociodemographic and geographic levels

Example of **different trip distributions by household type**

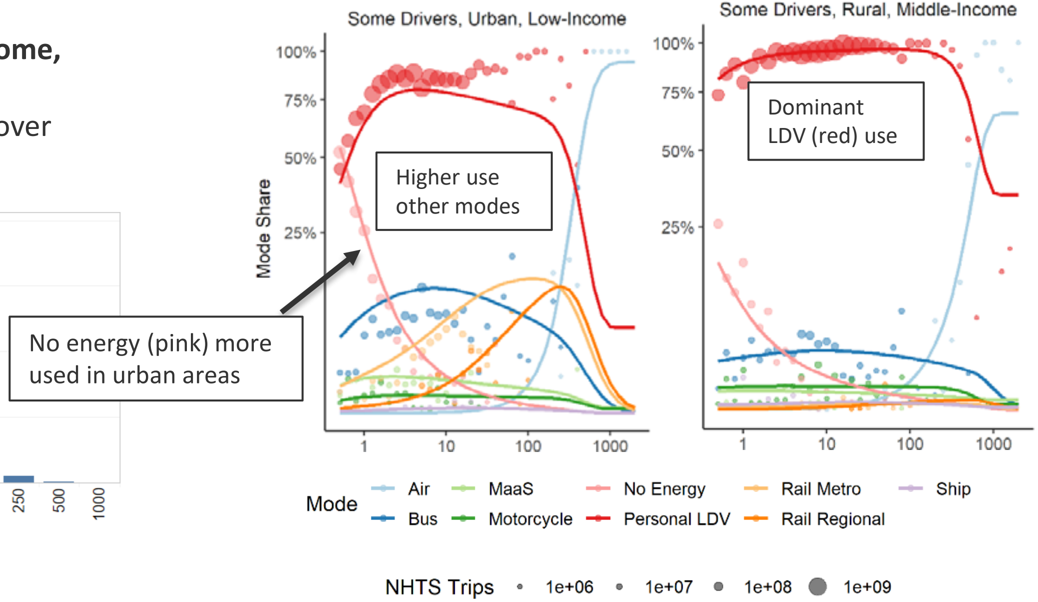
Smaller, low-income, urban household
- High proportion of short-distance trips

Larger, middle-income, rural household
- Trips distributed over greater distances



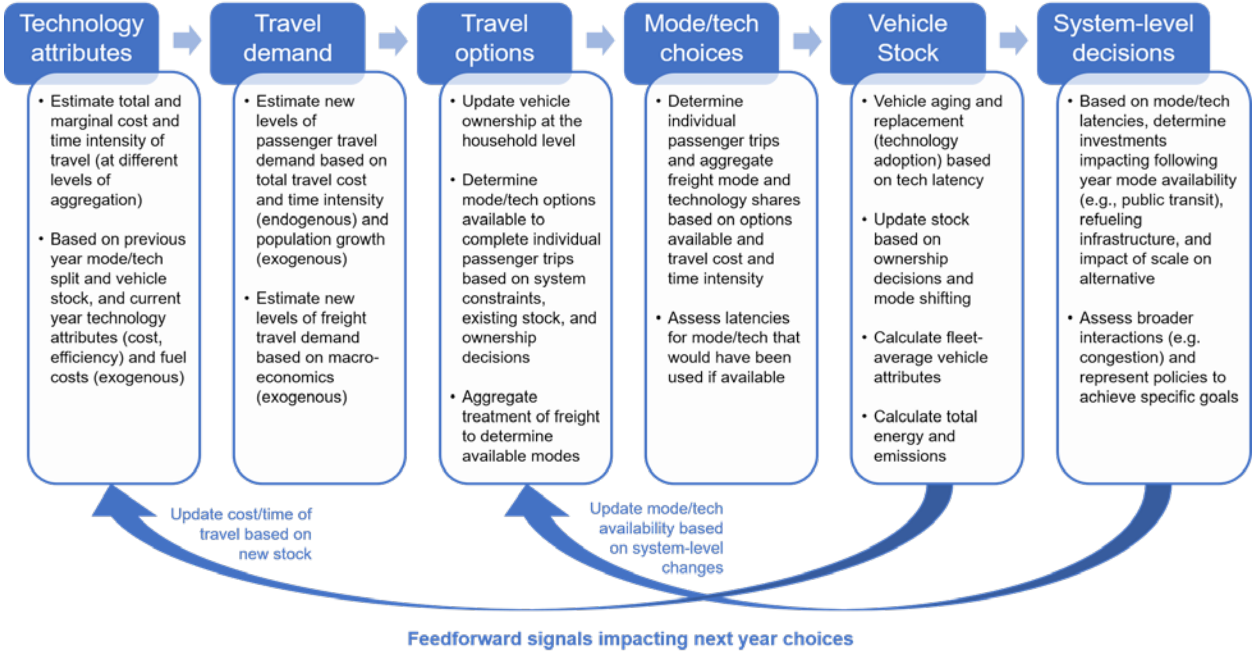
Example of **mode choice by household type**

TEMPO mode calibration (lines) compared to NHTS data (dots) share



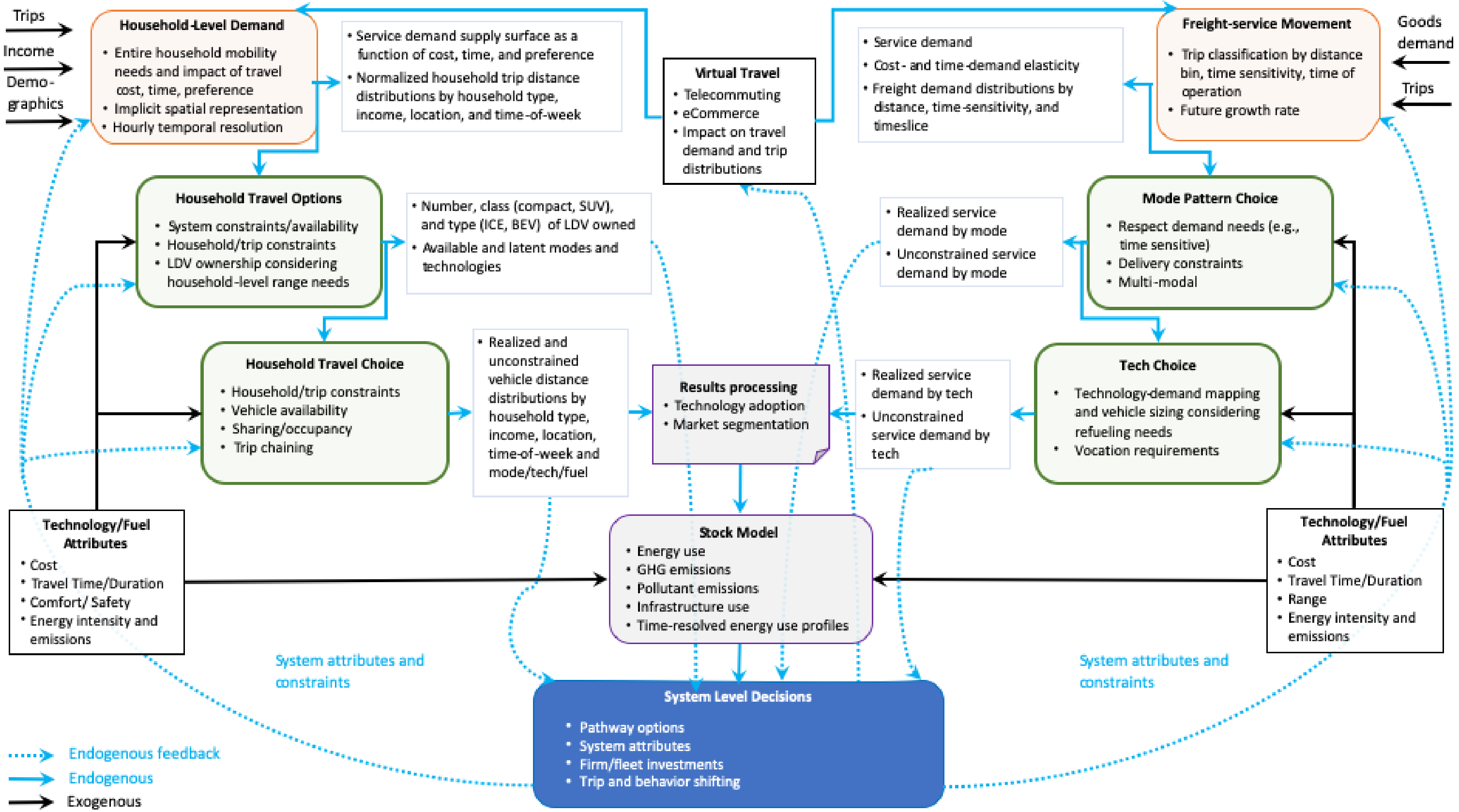
TEMPO Flow Diagram

TEMPO

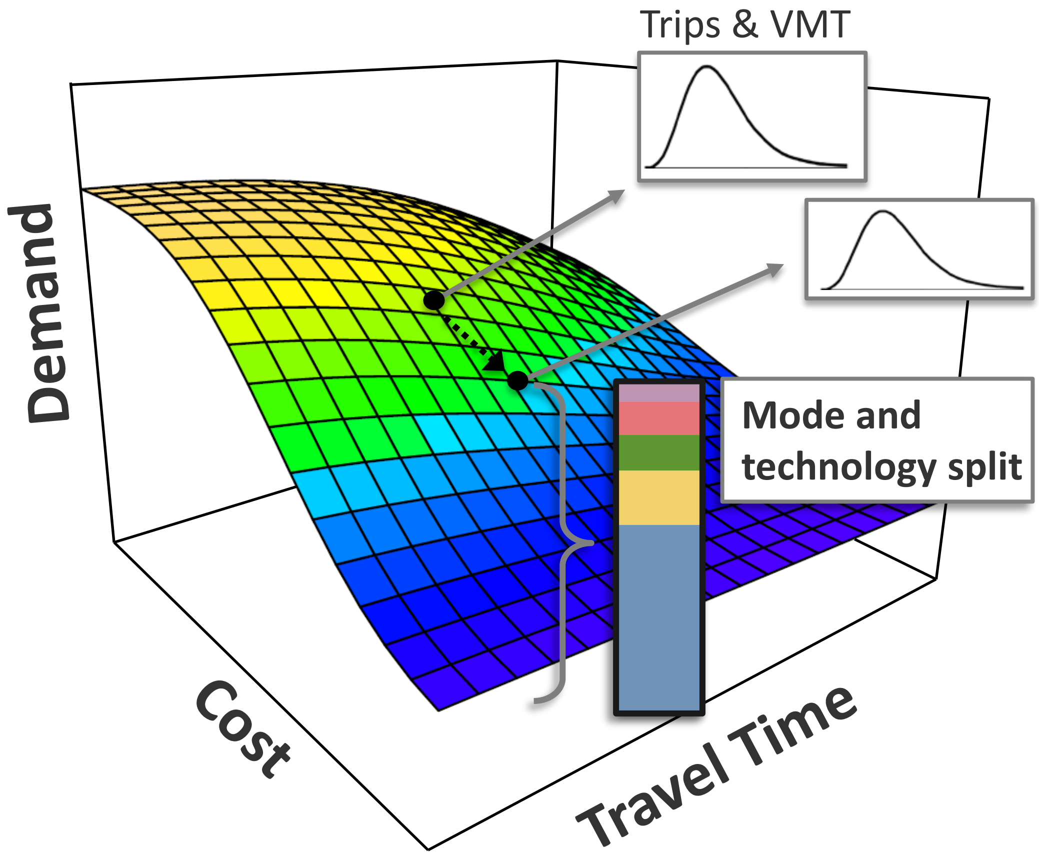


- Sequenced algorithmic cycle executed **for each model year (top arrows) in each region and for each demand bin.**
- Exogenous signals (e.g., policies) and choices impact options and choices modeled in subsequent years via feedforward signals (bottom arrows).
- For example, latency in a specific mode/technology spurs investment that helps realize those latencies, which is reflected in following iterations.

TEMPO Scheme



Example of Model Logic (Passenger Demand)

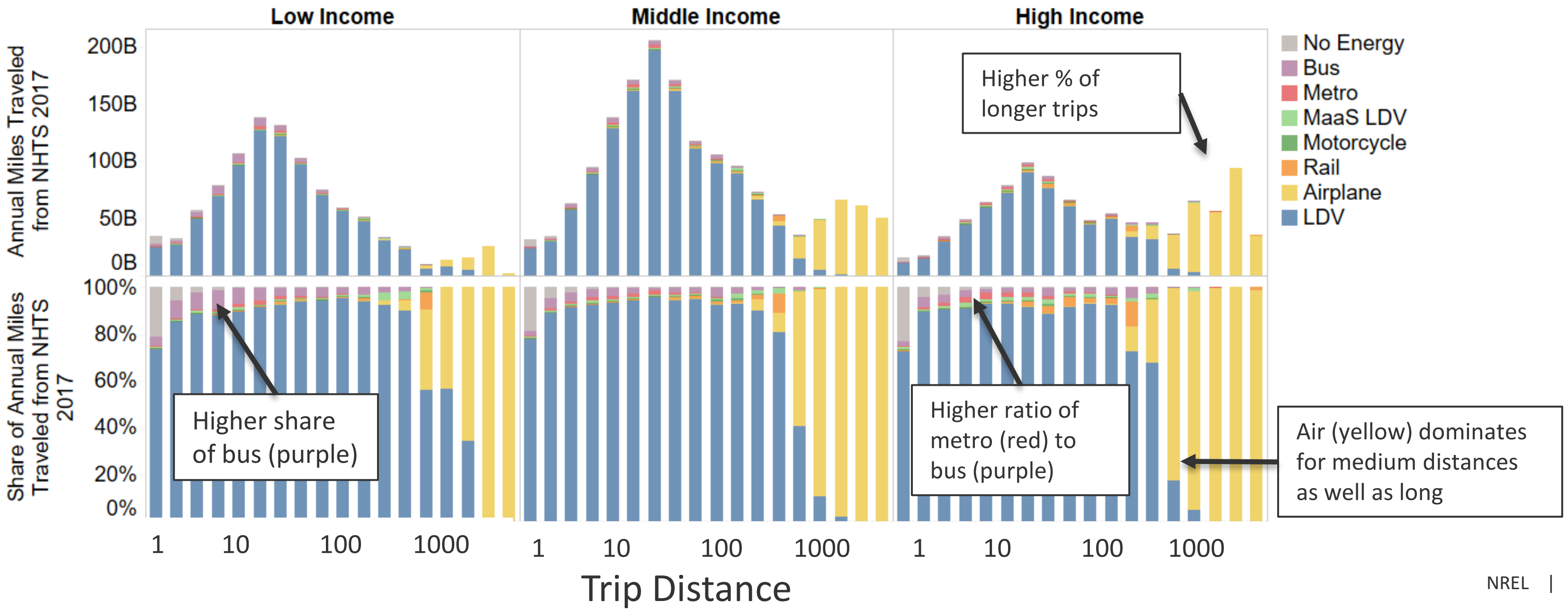


- The surface represents **total household travel demand,** determined by travel cost, time, and other factors (monetized) for each household bin
- Each point on the surface represents a **distribution of trips and trip distances**
- Changes in travel cost or time result in a **shift along the surface**
- **Mode and technology split** is estimated for each demand point distribution using a calibrated logistic model

Passenger Mode Choice

TEMPO

TEMPO represents distinct trip choices across household bins. For example, **trip distributions and mode choice vary with household income**.



Example of Model Logic (Freight)

TEMPO

- Freight demand growth is set exogenously, based on external macroeconomic drivers (e.g., GDP)
- Mode choice per freight bin based on historical mode splits for the initial version of TEMPO to capture logistics constraints (e.g., railways)
- Technology choice decisions are made per freight bin based on time and cost intensity of available technologies.

$$w_t = \alpha_t \, e^{\left(\frac{-K_1 C_t^{total} L}{Cap_t \, Load_t} - \frac{K_2 T_t \, L}{Cap_t \, Load_t}\right)}$$

$$s_t = \frac{w_t}{\sum_{t=1}^{T} w_t}$$

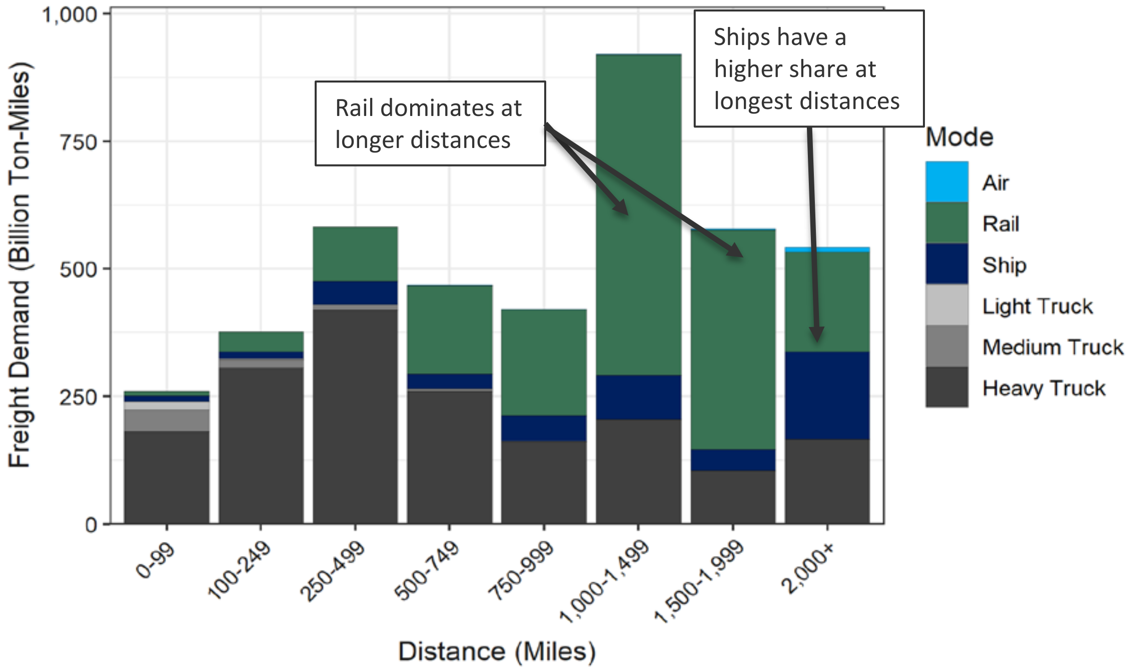
w_t = weight for technology t
s_t = expected share for technology t
α_t = logit calibration coefficient for technology
C_t^{total} = average marginal cost intensity of travel (\$/mi) for technology
T_t = average time intensity of travel (hr/mi) for technology
K_1 = cost logit parameter for the given freight bin
K_2 = time logit parameter for the given freight bin
L = trip length (mi) based on the freight bin distance dimension
Cap_t =average capacity (tons/vehicle) of technology t
$Load_t$ = average load factor (ton/ton) of technology t
T = all available technologies

Freight Mode/Tech Choice

TEMPO

TEMPO represents travel choice across freight bins. For example, **mode and technology choice varies with average shipment distance**.

Freight demand by fuel derived from 2017 AEO 2019 and FAF data used for TEMPO calibration.



INPUTS AND MODEL VALIDATION

Why should you "believe" TEMPO results

TEMPO Relies on Myriad of Data Sources

TEMPO

Passenger Data Sources

Module	Data Element	Data Source(s)
Household-level travel demand	Travel demand distributions	FHWA (2018)
	Travel demand elasticities	(Börjesson, et al. 2012; de Jong and Gunn 2001; FHWA 2018; USDOT 2016a; Wadud, Graham, and Noland 2009b)
	Households (current and projected)	FHWA (2018)/EIA 2019
Household Travel Options and Household Travel Choice	Vehicle ownership	FHWA (2018)
	Logit coefficients	Calibrated (EIA 2019, FHWA 2018)
	Occupancy factors	FHWA (2018), BTS (2017b), USDOT (2019)
	LDV size class distributions	FHWA (2018), EIA (2019)
Household Technology Attributes	Technology costs	EIA (2019), USDOT (2019), BTS (2017a), NREL (2019)
	Technology fuel economy	EIA (2019), NREL (2019)
	Technology time intensity	FHWA (2018)
	Fuel costs	EIA (2019)
	Emissions factors	GREET Model (ANL 2019a)
Household Stock Model	Initial stock	Polk IHS
	Initial fleet average fuel economy	EIA (2019)
	Survival rates	Jacobsen & Benthem 2015

Freight Data Sources

Module	Data Element	Data Source(s)
Freight demand	Travel demand	FHWA (2019), EIA (2019)
Freight Mode Choice and Freight Technology Choice	Logit coefficients	Calibration
	Load factors and Capacities	CAVIUS (Khan et al. 2019), TEDB (Boundy 2019), Martland (2013), Grenzeback et al. (2007), USDOT Maritime Administration (MARAD 2019), Kruse et al. (2017), USACE (2018)
Freight Technology Attributes	Technology costs	EIA (2019)/ATB
	Technology fuel economy	EIA (2019)/ATB
	Technology time intensity	FHWA (2005), BTS (2017b), King et al. (2008)
	Fuel costs	EIA (2019)
	Emission factors	GREET Model (ANL 2019a)
Freight Stock Model	Initial truck stock	EIA (2019)
	Initial fleet average fuel economy	EIA (2019)
	Survival rates	VISION Model (ANL 2019b)

Input Data Processing: Freight Example

- **Goal:** represent freight accurately in TEMPO with quality data inputs
- Problems:
  - disagreements across sources/models
  - Gaps in key metrics, time periods, modes.
- Solution(s) often require **merging multiple datasets** to meet desired input data needs.

FAF → Total ton-miles and Avg trip distance by distance bin

↓

VIUS → Percent of ton-mi by truck class within distance bin

↓

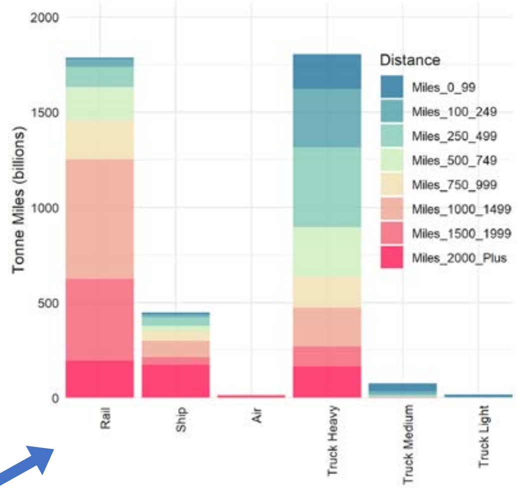
Total ton-mi by truck class within distance bin

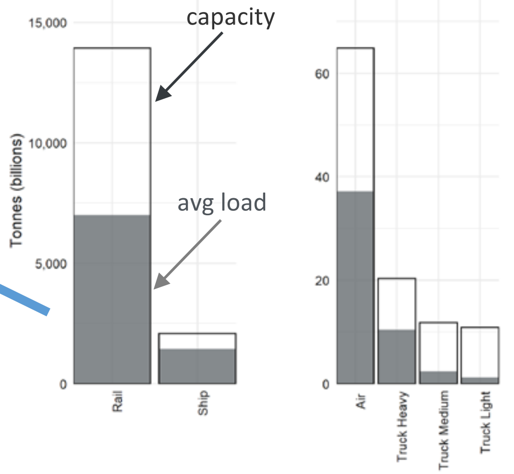
↓

VIUS → Avg load (incl. deadhead) by truck class within distance bin

↓

Total VMT by truck class within distance bin

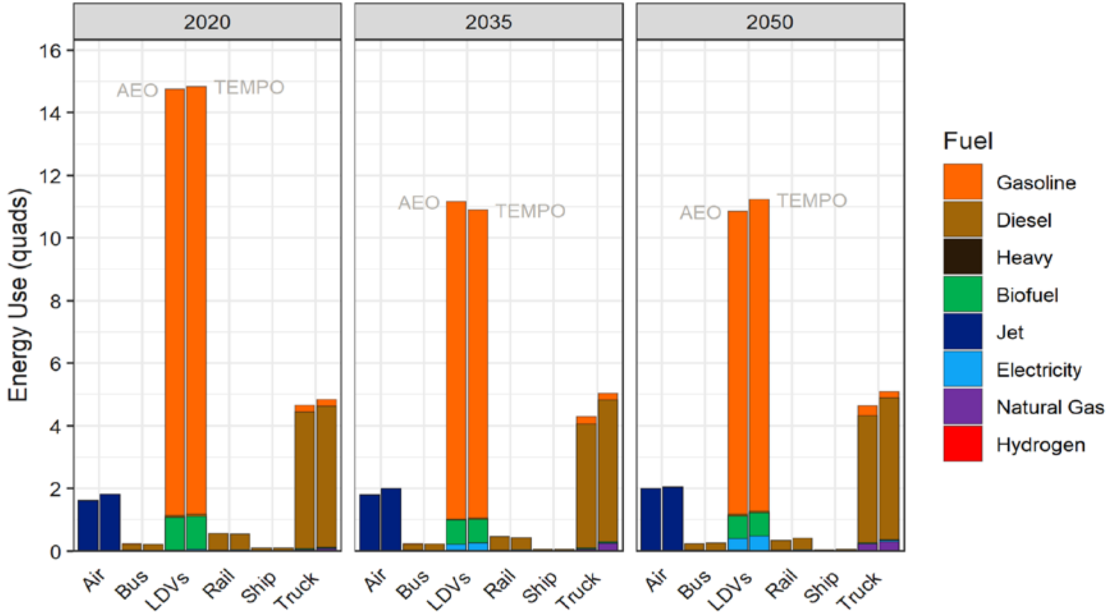




Validation: Energy Use

TEMPO

Validating future projections is an "impossible" task. Comparison with EIA AEO illustrates the **ability of TEMPO to represent the key elements that determine future energy use at the appropriate level of resolution**.



TEMPO energy use estimates by mode, technology, and fuels within 5% of AEO projection in every modeled year.

Note: Technology adoption is calibration to match AEO results and do not reflect the TEMPO "reference" scenario.

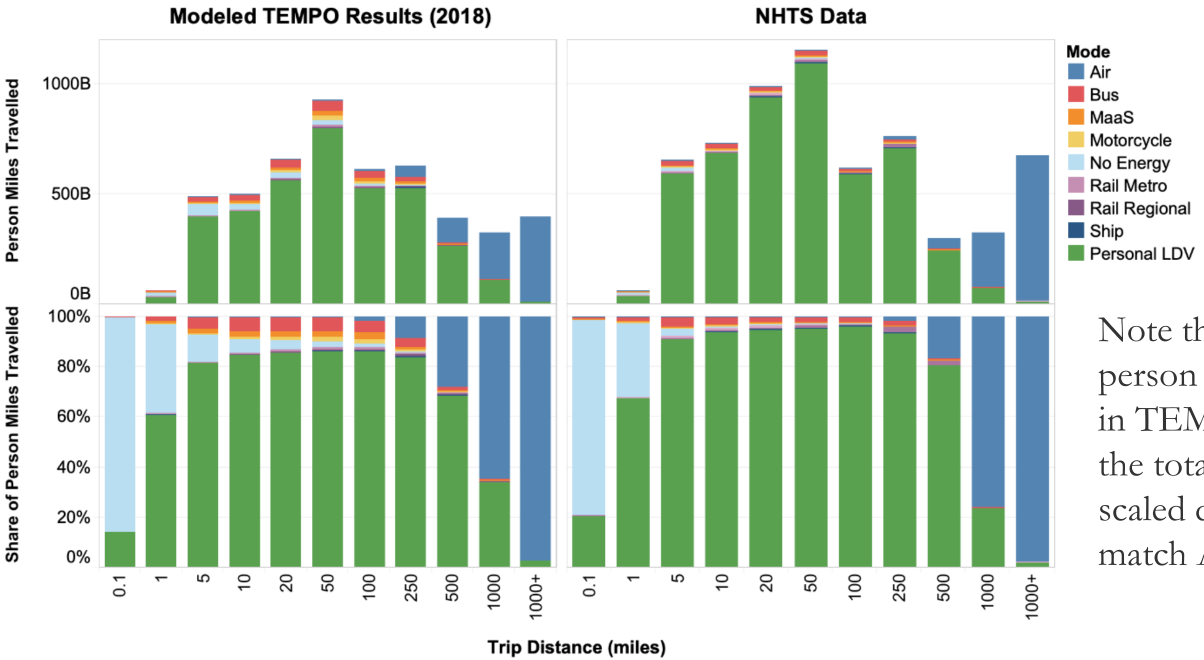
Why calibrating/validating with AEO?

- **Validating future projections**, especially major changes from the status quo that may happen for mobility systems over the coming decades, is an impossible task
- However, it is important to illustrate the **ability of TEMPO to accurately project future scenarios and represent the key elements** that determine future transportation energy use at the appropriate level of resolution
- AEO provides **comprehensive and widely accepted projections**
- By supplementing some exogenous TEMPO inputs with consistent AEO-based assumptions and calibrating the TEMPO technology adoption logit formulation to AEO projections, we **validate that TEMPO properly represents and allocates travel demand, energy use, and vehicle stock evolution by fuels, modes, and vehicle types**
- **TEMPO was calibrated in 2017** based on multiple data sources, including NHTS 2017 for passenger demand and FAF 2017 for freight demand.

Note: TEMPO is validated against the 2019 AEO because it is the latest AEO with model year 2017 to be compatible with the rest of TEMPO inputs.

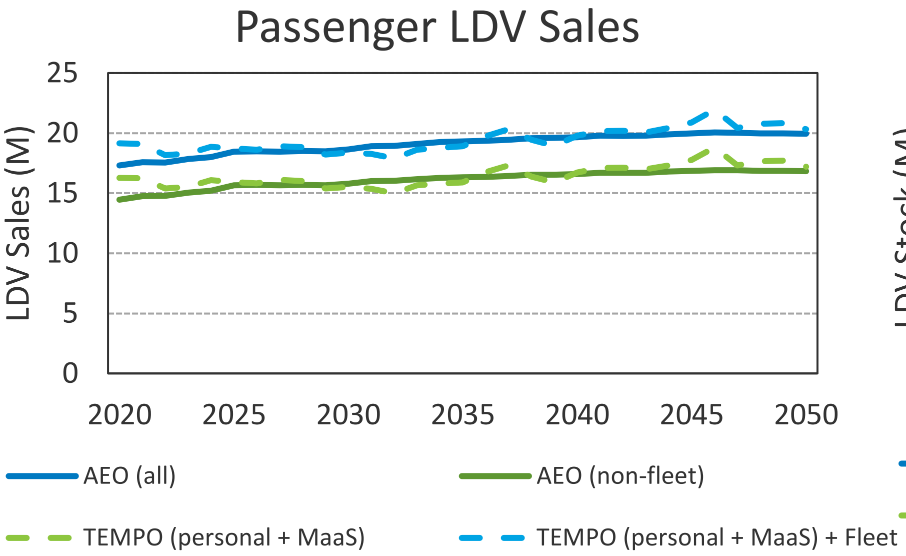
Passenger Mode Choice

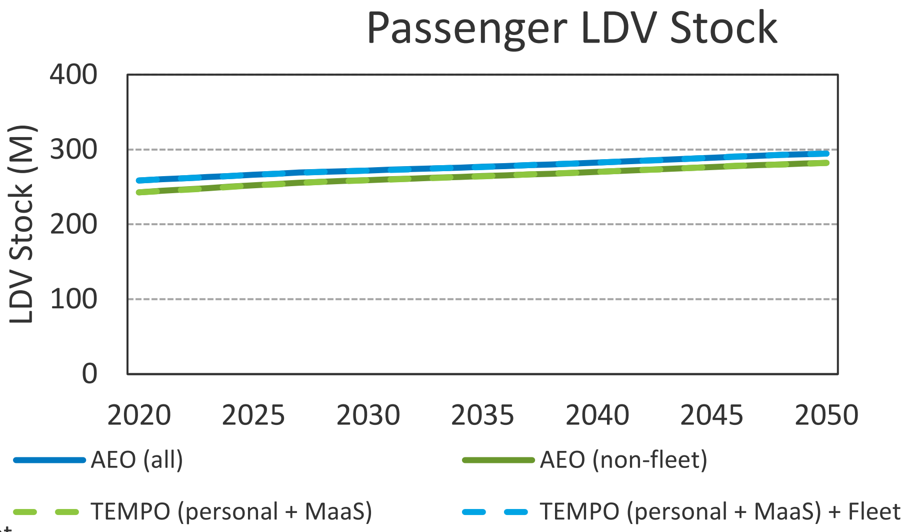
TEMPO properly represents the complex and heterogeneous passenger travel behavior by matching travel demand and mode choice over varying trip distances.



Note that while the distribution of person miles travelled by distance bin in TEMPO matches that in NHTS, the total person miles travelled is scaled down compared to NHTS to match AEO

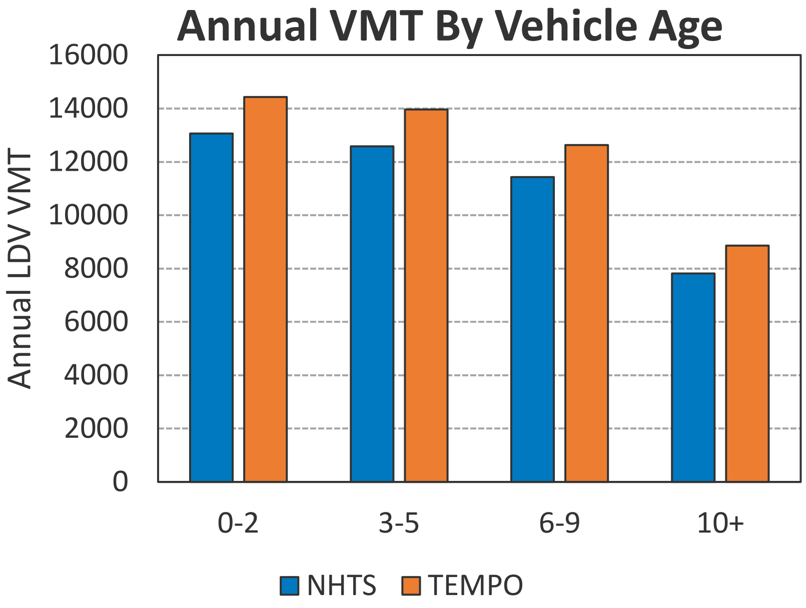
Passenger Light-Duty Vehicle (LDV) Sales and Stock

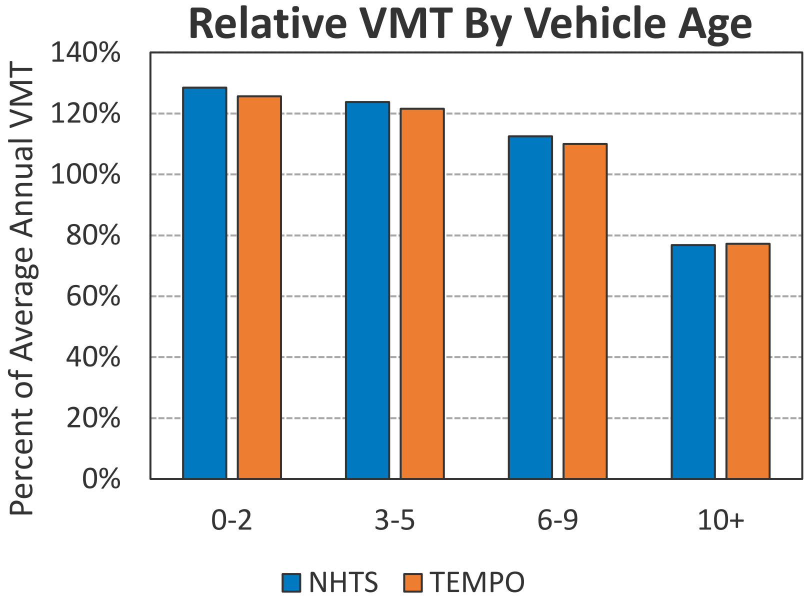




- Total passenger **LDV sales projected in TEMPO based on population growth, endogenously evolving passenger travel demand needs, vehicle ownership and mode choice decision, and vehicle retirements**
- Good alignment with other projections, this scenario doesn't consider major mobility changes like major to shifts to on-demand or shared mobility
- Total passenger **vehicle stock well aligned with AEO projections**
- Commercial light trucks (not plotted) are an additional ~0.9M sales per year / 19M stock in 2050

LDV Usage by Age





TEMPO's relative vehicle use distributions by age are well aligned with NHTS[1]

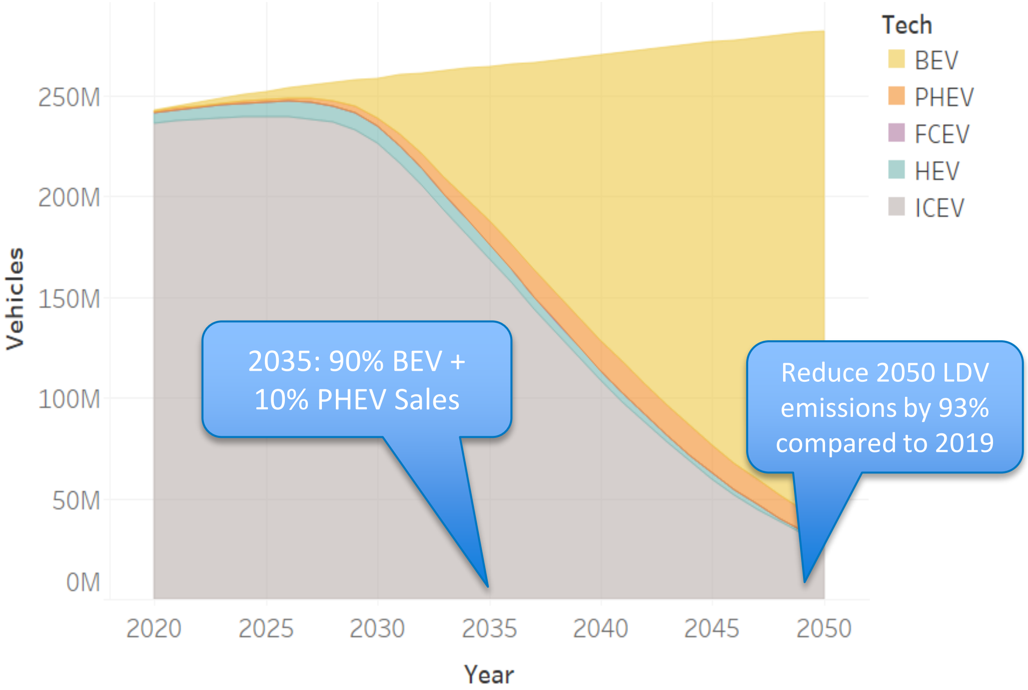
[1]McGuckin, N. and Fucci, A. 2018. Summary of Travel Trends: 2017 National Household Travel Survey. Table 22: Trends in the Average Annual Miles per Vehicle by Vehicle Age (Vehicle Owner's Estimate). Federal Highway Administration, FHWA-PL-18-019.

EXAMPLE RESULTS

100% EV sales by 2035 reduces emissions by 93%

TEMPO

- TEMPO allows users to quickly model the impacts of a rapid **increase in EV sales**
- **Example scenario: 50% EV sales by 2030**, and **100% by 2035—**supported by expanded charging infrastructure; rebates; manufacturing and supply chain investments; and other efforts
- Without major mobility changes (e.g., shift to MaaS and drop in LDV ownership, higher vehicle occupancy, etc.), **100% EV sales by 2035 leaves 28M (10%) ICEV on the road in 2050 and reduces 2019 LDV emissions by 93%.**

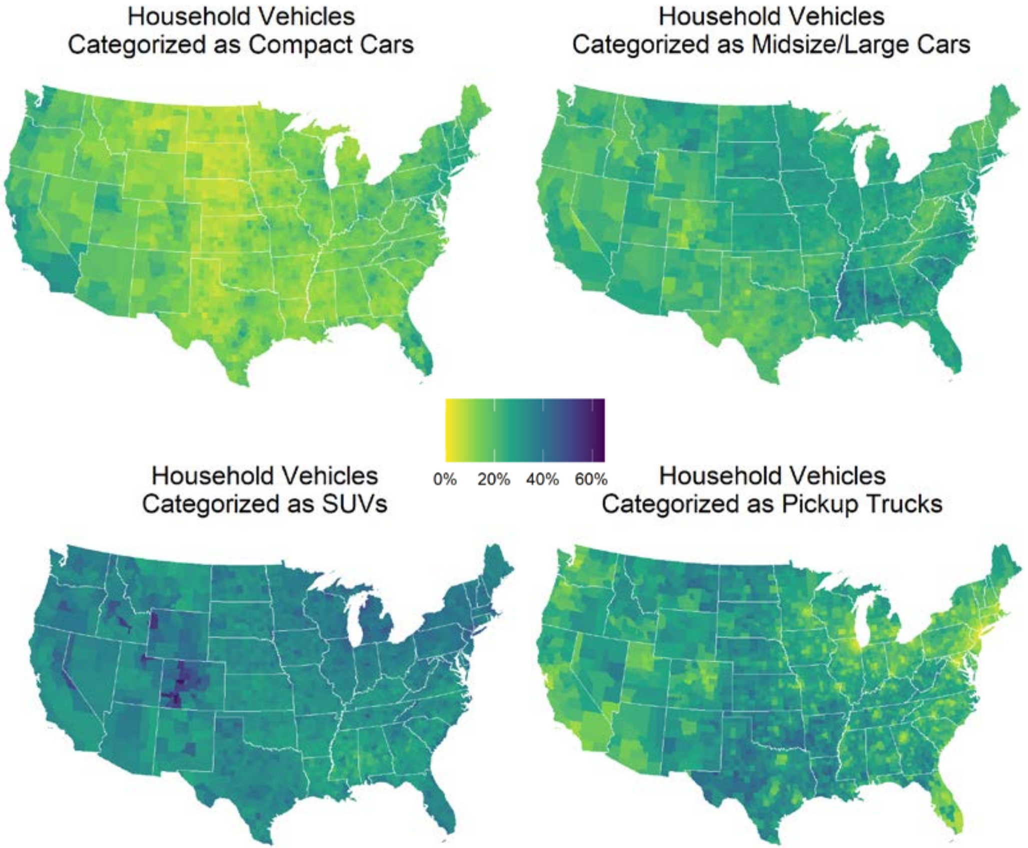


Includes personal LDV & MaaS. Fleet vehicle stock not included.

TEMPO accounts for unique vehicle class preferences by household type and by county

TEMPO

- **Vehicle energy usage depends on vehicle attributes and preferences,** such as vehicle size class and associated fuel economy
- Electrification opportunity is also affected by vehicle size class
- TEMPO captures these differences in vehicle preferences attributes by household type and county

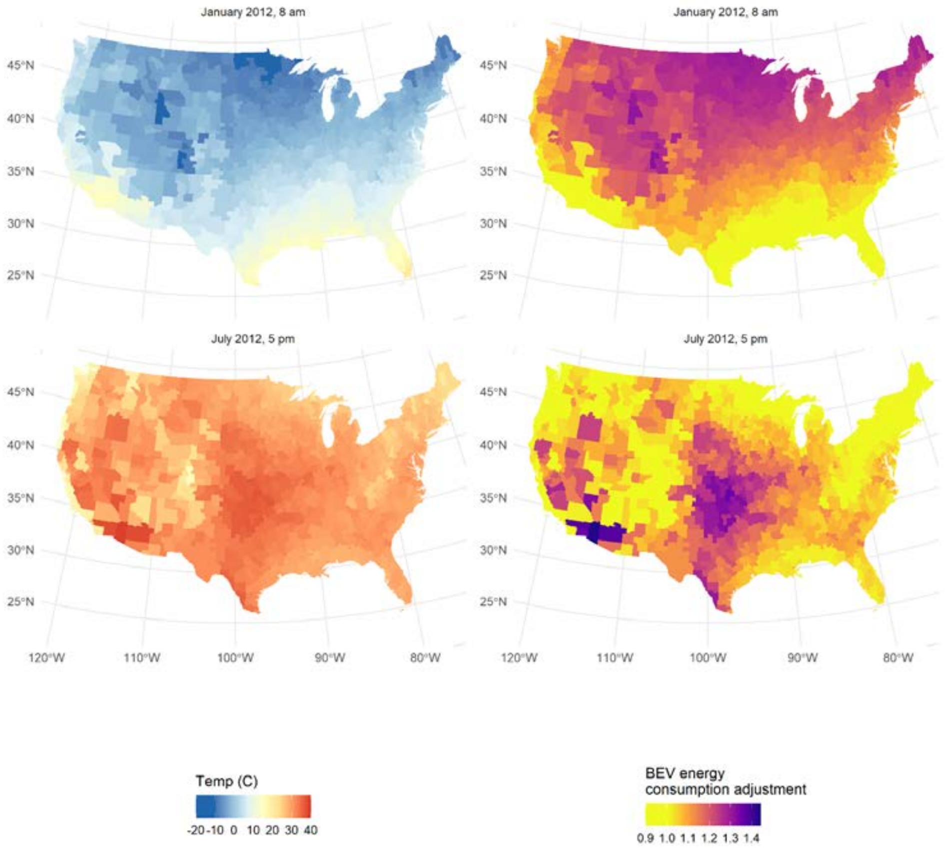


Data Source: IHS

TEMPO captures annual temperature effects on vehicle energy use and charging by county

TEMPO

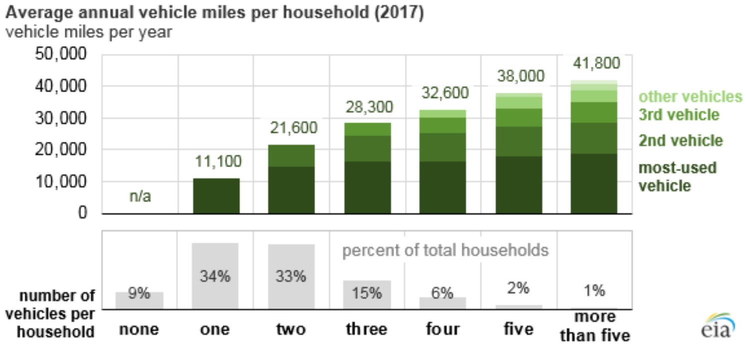
- **Vehicle energy usage depends on ambient temperature**, that changes over time and for different locations.
- **BEVs are disproportionately affected**: the energy used to drive a mile can change by up to 50% at temperature extrema, heavily impacting vehicle range, charging needs, cost of driving, and consumer experience.



TEMPO captures nuances needed to better estimate energy use/emissions implications

Not all vehicles are equal, and *X* EVs on the road can lead to widely different impacts. **TEMPO's unique representation of household travel demand provides new insights on adoption opportunities and energy/emissions implications**. Several factors determine energy use and emission benefits:

- **Vehicle use**: in a 2-vehicle household (33% of household), the primary vehicle is driven ~2X of the 2nd vehicle
- Different **vehicle classes** have +-40% fuel economy
- **Household bins (composition, income & urbanity)** have substantial variation in driving behavior (~70% more VMT between highest and lowest bin)
- **Location**: different vehicle classes distributions greatly and different temperatures impact energy use over the year
- **Charging** location and timing is critical for grid integration.



Source: EIA based on NHTS data

TEMPO's unique representation of household travel demand provides new insights on EV adoption opportunities and energy/emissions implications

- **Heterogenous household travel representation:** EV adoption is differentiated across households (income, household composition, geography), where EVs may be more or less suitable to different households based on travel patterns, vehicle class, and preferences

- **Modeling of household "fleets"**: Compared to modeling individual vehicles, representing a "fleet" of household vehicles enables to match vehicles range with mobility needs, for example, targeted adoption of shorter-range BEVs, providing more realistic adoption opportunities

- **Mode choice and impact on vehicle ownership**: TEMPO captures new business models (e.g., MaaS) that are impacting ownership decision and introduce new use profiles that impact adoption. High vehicle utilization in MaaS fleets, for example, increases electrification benefits

- National, annual average fuel economy and energy efficiency metrics can obscure variation in vehicle energy use in different locations and at different times of day and seasons of the year. TEMPO captures **annual temperature effects on vehicle energy use** and charging by county

- **High temporal resolution:** hourly resolution allows for coupling to grid models to estimate the impact of charging time and incorporate the resulting hourly electricity prices and emissions profiles into adoption decisions and model resulting.

CONCLUSIONS

Summary of TEMPO

TEMPO

- Model **transportation energy use and emissions**, especially for alternative scenarios (technological breakthroughs and/or new business models) or to find pathways to the desired goal
- Includes key modeling elements to explore future scenarios:
  - Scope includes **both passenger and freight**, representing the majority of transportation energy
  - Spatiotemporal representation ensures rapid model execution but provides **enough resolution to integrate with supply-side models**
  - **Household-level decision-making** facilitates distinct choice characteristics across different geographic/sociodemographic categories and trip choice among vehicles with diverse attributes
  - Feedbacks allow for **endogenous evolution of travel options and travel choice** based on demand (realized and latent) and external drivers (e.g., policy)
- **<u>Enables important analyses</u>**:
  - Market segmentation and market potential for future technologies and business models
  - Integration of transportation and electric sectors
  - Impact of external drivers (e.g., technology cost, policy) on technology adoption.

What questions can TEMPO answer?

TEMPO

MAJOR PRIORITY	EXAMPLE QUESTION
Market segmentation across modes and technologies	What is the role of different fuels in future transportation systems across multiple subsectors and market segments (e.g., long-haul trucking), and what are the tipping points?
Demand-supply integration (spatiotemporal demand resolution)	What are the hourly electricity transportation demand profiles, and how will they affect the power grid, especially renewables?
Role of automation and new business models (MaaS, micro-mobility)	How does automation affect transportation demand, and what would be the impact of new business models?
Explore and represent policy scenarios, inform R&D investments	How do R&D investments affect the evolution of the energy supply and transportation system?
Design scenarios to explore uncertainty and overcome lack of data	How to design scenarios relevant to multiple stakeholders, and how to use them to overcome lack of data (what is endogenous vs. exogenous)?
Role of refueling infrastructure	What is the role of infrastructure in technology adoption in the transportation space, and who pays for it?
Global and multi-sectoral or complex non-energy dynamics	How do changes in the economy affect transportation demand for goods and services?
Metrics needed to explore future transportation scenarios	What metrics are important beyond miles traveled?

References and Acknowledgement

TEMPO

- **Website**

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

- **Motivational paper**: why do we need TEMPO?

  Muratori, M., Jadun, P., Bush, B., Bielen, D., Vimmerstedt, L., Gonder, J., Gearhart, C. and Arent, D., Future Integrated Mobility-Energy Systems: A Modeling Perspective, *Renewable and Sustainable Energy Reviews, 119* (2020)

- **Model documentation paper**: how does TEMPO work (and validation)?

  Muratori, M., Jadun, P., Bush, B., Hoehne, C., Vimmerstedt, L., Yip, A., Gonder, J., Winkler, E., Gearhart, C. and Arent, D., Exploring the Future Energy-Mobility Nexus: The Transportation Energy & Mobility Pathway Options (TEMPO) Model, *Transportation Research Part D* (2021)

- **Factsheet: what is TEMPO?**

  Exploring the Future of Mobility: Transportation Energy and Mobility Pathway Options Model, NREL Fact Sheet (2020)

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Thanks! Questions?

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TEMPO Steering Committee

TEMPO

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TEMPO Modeling Attributes

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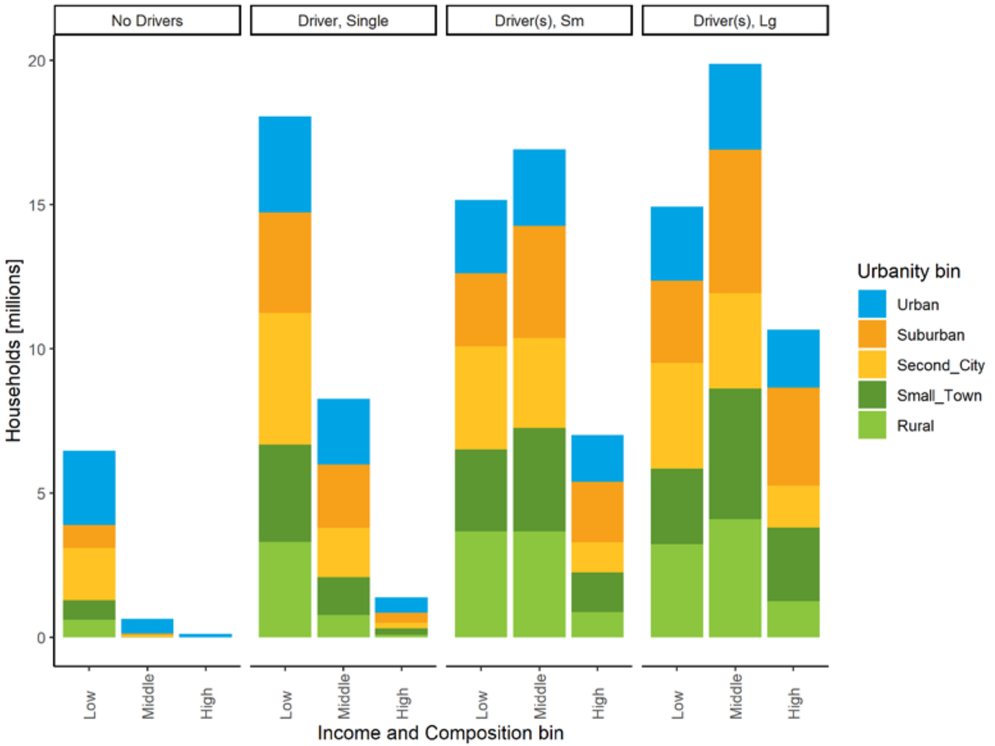
Desired modeling framework attributes:

- Customizable: represents today's baseline and alternative future scenarios
- Flexible: performs out-of-sample forecasting to extrapolate recent emerging trends
- Compatible and scalable: model/data structures compatible with SIIP and other NREL tools
- Appropriately sensitive: represents sub-sectoral detail and key metrics
- Useful and defensible: answers relevant questions and produces results consistent with and complementary to detailed bottom-up NREL models (*e.g.*, ADOPT, SERA, EVI-Pro, Smart Mobility)

Household Counts by TEMPO Demand Bin



TEMPO models households binned along multiple dimensions:

- **Composition** (number of household members and drivers)
- **Urban classification**
- **Income**

This allows TEMPO to represent **heterogeneity** of consumers and their travel needs/choices along these dimensions to estimate impacts for different regions/groups.

TEMPO incorporates patterns for vehicle size, class, and fuel economy

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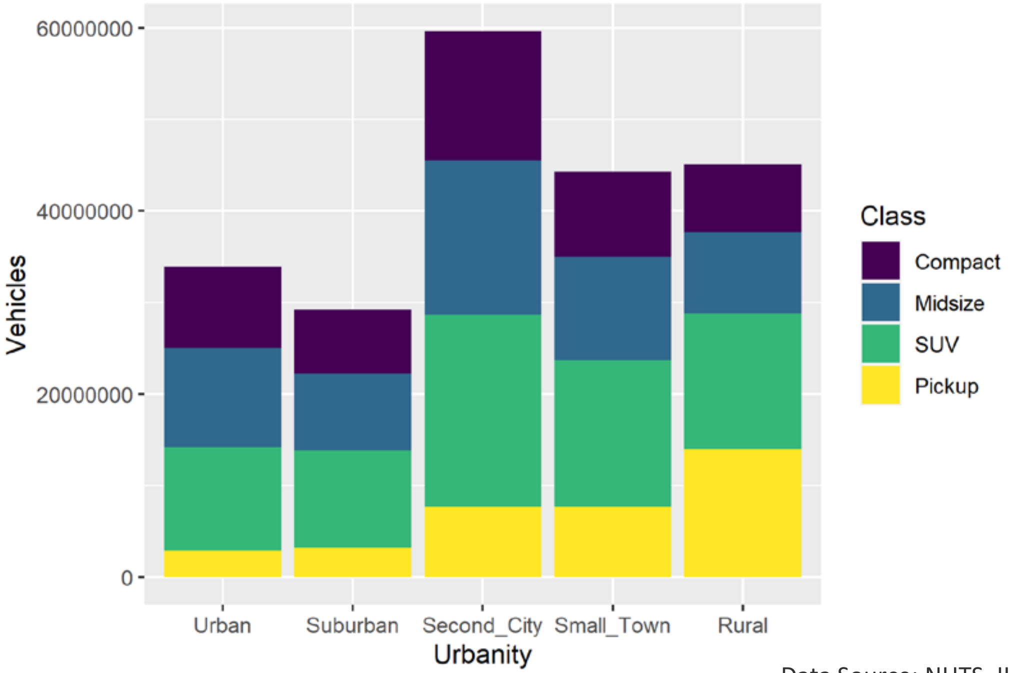
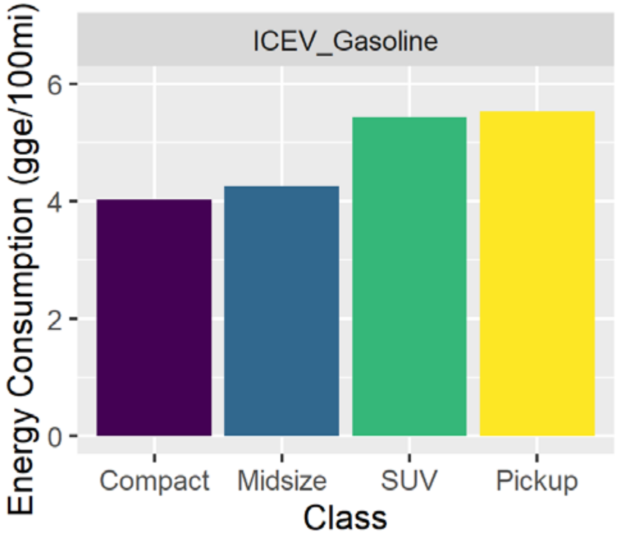
Vehicle class distributions are significantly different by urbanity



Vehicle classes have large implications on fuel economy and energy use



Data Source: NHTS, IHS

TEMPO corrects vehicle energy usage, according to temperatures specific to location, month, and time

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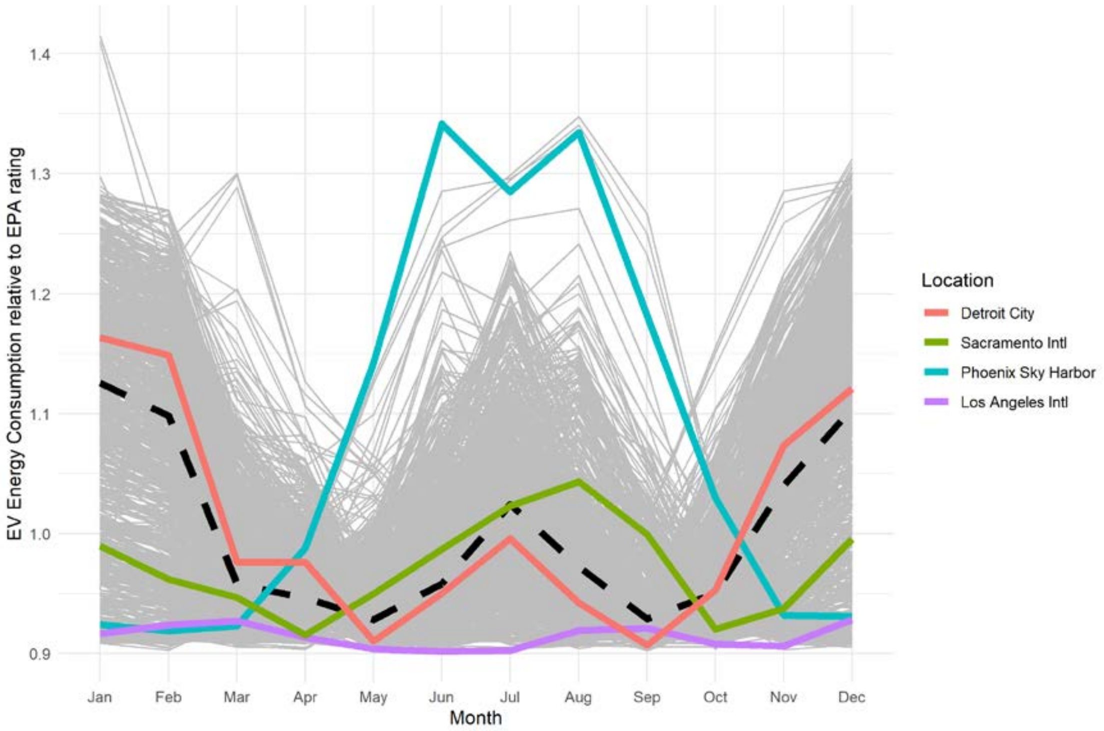
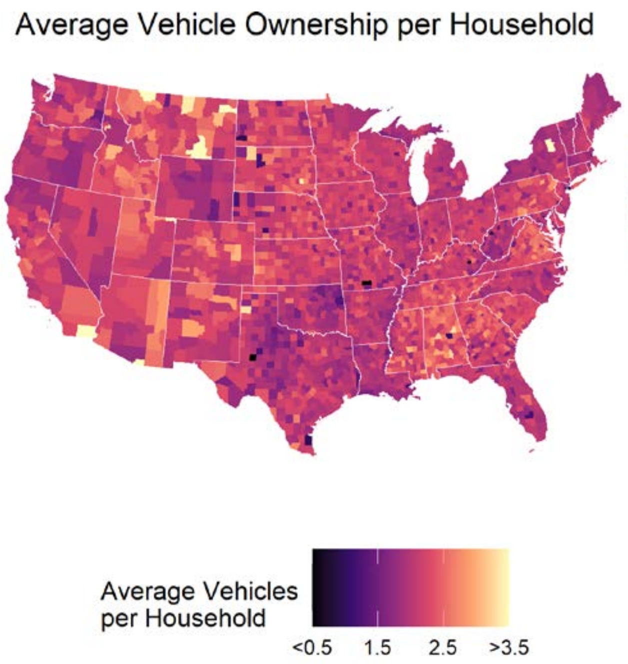
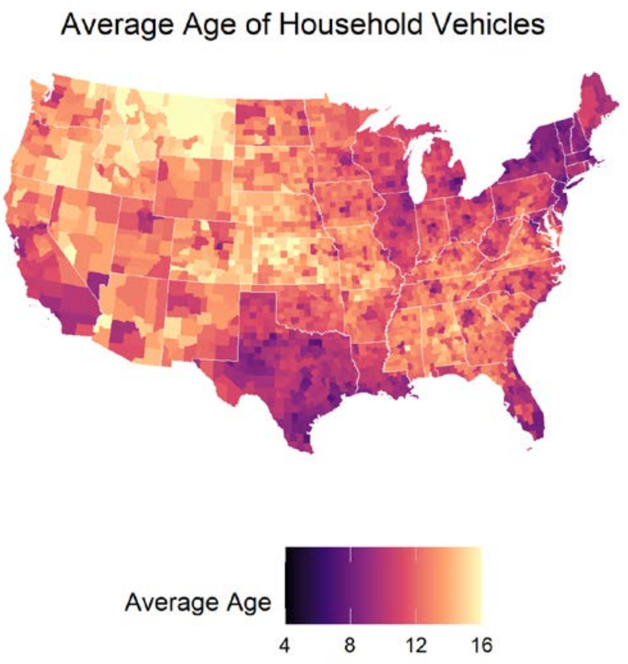
- **Vehicle energy usage depends on ambient temperature**, that changes over time and for different locations.
- **BEVs are disproportionately affected**: the energy used to drive a mile can change by up to 50% at temperature extrema, heavily impacting vehicle range, charging needs, cost of driving, and consumer experience.
- TEMPO captures **annual temperature effects on vehicle energy use** and charging by county.



Counties have unique vehicle ownership, affecting LDV use and substitution patterns



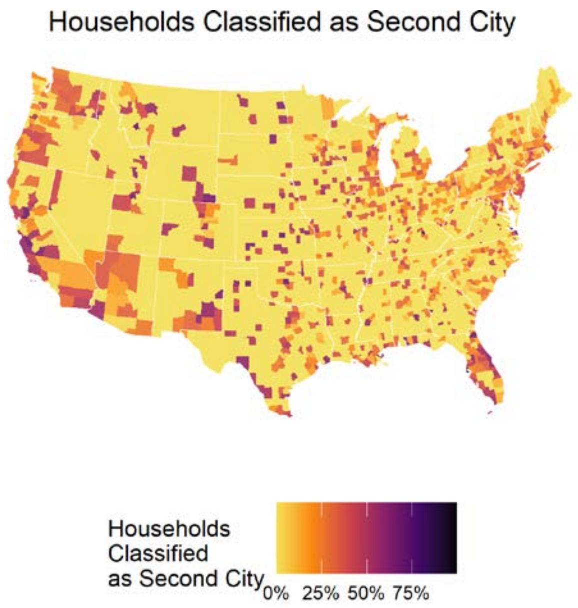


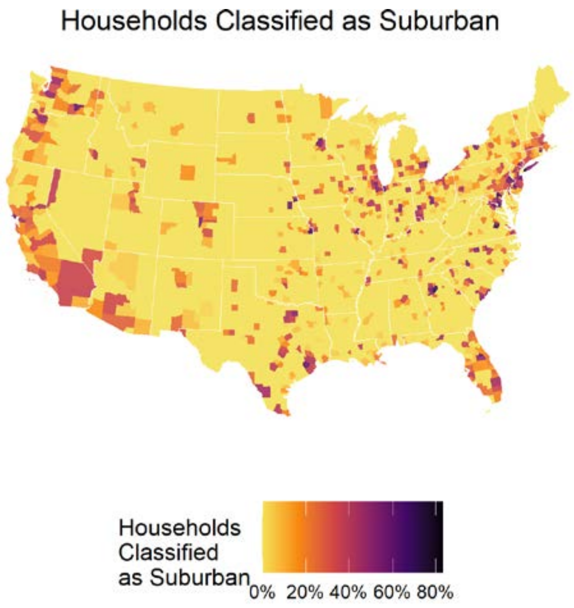
Important to capture these differences because:

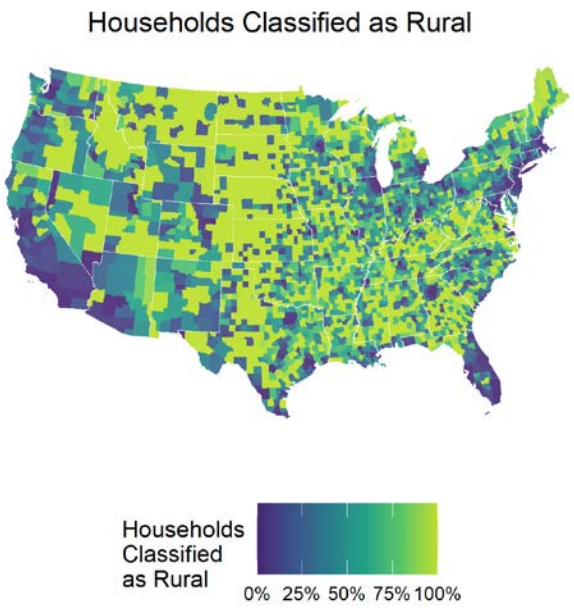
- Number of vehicles in a household affects travel options vehicle ownership, and technology adoption decisions
- Older vintage vehicles are less energy efficient

Data Source: ACS, PUMS, IHS

Counties have different mixes of households, affecting travel demand and preferences







Data Source: ACS/PUMS

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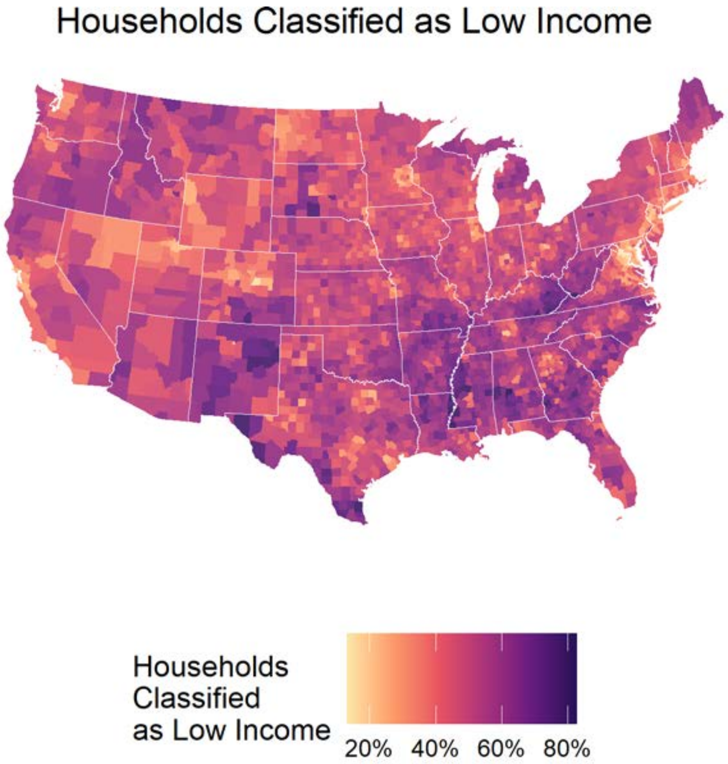

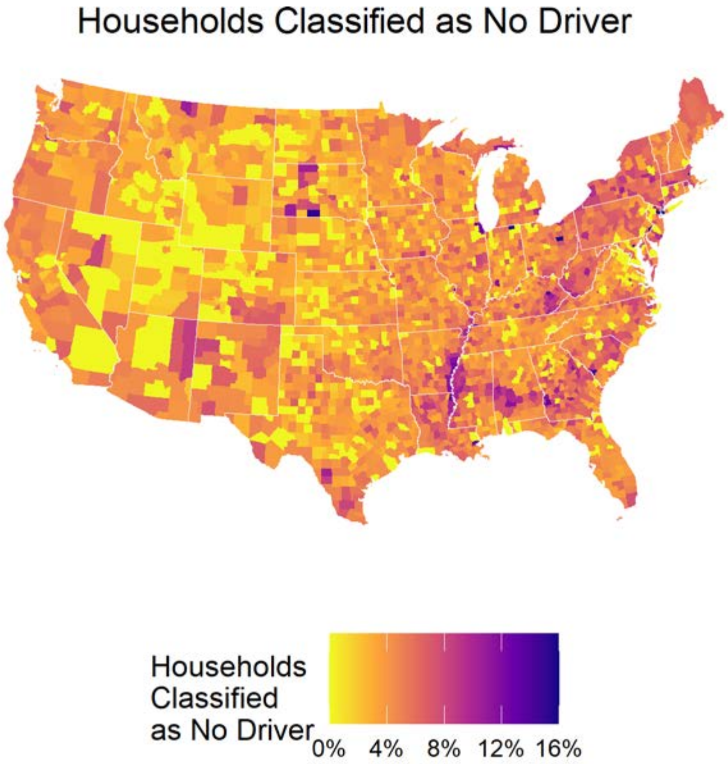

Data Source: ACS/PUMS