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Project title:	Quantifying New and Used Plug-in Electric Vehicle Market Dynamics in Disadvantaged Communities
Area of interest:	13: Transportation and Energy Analysis
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Locations of project work:	Washington, D.C.; Denver, CO.
Confidentiality statement:	The PI and team members have no confidentiality statements to make.

1. PROJECT OVERVIEW

Problem: Electrifying the vehicle fleet is a cornerstone of most plans to reduce greenhouse gas emissions causing climate change, but plug-in electric vehicles (PEVs) are still not accessible for most car buyers in the U.S. Even with financial incentives, prices are still significantly higher for most PEVs relative to comparable internal combustion engine vehicles (ICEVs)[1], and buyers who lack dedicated parking spaces may struggle to find a place to regularly charge. As a result, the majority of PEVs sold in the U.S. have been purchased by wealthier buyers who typically have dedicated parking spots or garages at home to charge their vehicles overnight[2]. Policy interventions will be needed to make PEVs more accessible to disadvantaged communities (DACs), but little is known about the needs and preferences of these communities as well as the market dynamics governing the used vehicle market—where most people in DACs buy vehicles. By improving our understanding of the dynamics governing these markets, we will be able to design more effective and equitable policies and incentives to accelerate PEV adoption in DACs.

Relevance to AOI objectives: This proposal directly addresses the lack of knowledge pertaining to new and used plug-in electric vehicle market dynamics in DACs—one of the focal gaps recognized in AOI 13. This project will generate new data and insights on the needs and preferences of vehicle owners as well as barriers to increasing PEV adoption in DACs. The project will also generate new analytical models for understanding market dynamics between the new and used vehicle markets—an under-studied relationship that is critical for vehicle affordability. These outcomes are aligned with the AOI 13 objective of developing analytical models and applied analyses to help identify pathways to increase PEV adoption in DACs.

Project Approach: We aim to identify answers to the following research questions:

1. What are the geospatial and longitudinal trends of vehicle diffusion from the new to used market? Are PEVs diffusing similarly to ICEVs, and is that diffusion different in DACs?
2. How are PEVs depreciating in value over time compared to ICEVs, and what (if any) impact have incentive policies (such as subsidies) had on that value?
3. What are the needs and preferences of disadvantaged and lower-income communities with respect to vehicle ownership in general and specifically for PEV ownership?
4. What are the equity implications of the above questions? Are new and used PEVs equally available (both in terms of location and affordability) in DACs compared to in other communities?

We will address these questions via two primary research thrusts involving (1) an analysis of a large dataset of new and used vehicle listings capturing nearly every vehicle sold at dealerships in North America between 2015 and 2023, and (2) interviews and choice-based conjoint surveys of car buyers and dealerships in DACs. The research thrusts will be conducted in parallel, with initial *exploratory* tasks for each thrust being conducted in the first budget period and later *confirmatory* tasks for each thrust being conducted in the second budget period.

Research Thrust 1: Measuring and Modeling Market Dynamics for New and Used PEVs

This thrust is aimed at addressing research questions 1, 2, and 4. In a partnership with cars.com, we have already obtained access to approximately 900 million records of daily new and used vehicle listings covering nearly every U.S. dealership from 2015 to 2023, a period during which approximately 85% of all PEVs ever sold in the U.S. were listed. Combined with registration data provided by NREL and other publicly available data, such as gasoline prices, demographic data, and historical PEV incentives, this data set presents an unprecedentedly

high-resolution lens into market outcomes of PEVs competing with ICEVs in the new and used markets as well as the spatial diffusion patterns of PEV adoption.

These data will be used to obtain key estimates of market characteristics and dynamics, including (but not limited to) *(1)* the supply of new and used vehicles to the market (e.g., where have automakers supplied the market as well as where vehicles go from the new to used markets), *(2)* depreciation rates of every vehicle make and model, *(3)* the potential impact of different incentives on PEV residual value, and *(4)* the length of time every new and used vehicle make and model remains on different dealer lots as a proxy for underlying demand, all else being equal. The team will use these data to conduct initial exploratory analyses of PEV spatial diffusion patterns over time as well as regression analyses to quantify the above market characteristics. The team will integrate robust results from these analyses into the Electric Vehicle Infrastructure for Equity (EVI-Equity) tool developed by NREL to characterize the equity impact / implications of the findings in different communities[3].

One benefit of using listings data is that it provides a novel window into the *supply* of vehicles. Automakers may supply more PEVs to states with more pro-PEV policies, such as states with purchase subsidies and states that have adopted the "Zero Emission Vehicle" (ZEV) mandate, which requires automakers to sell ZEVs in those states. We may be able to quantify this potential effect by exploiting the timing of when different states implemented the ZEV mandate. We can also use the days a vehicle remains listed as a proxy for demand. We will apply a variety of estimation strategies to obtain estimates of different parameters of interest. The detailed vehicle and location specifications in the listings data will enable us to control for a variety of important factors that influence listing prices, including state subsidies and other PEV policies, as well as other vehicle specifications (e.g., mileage).

Research Thrust 2: Measuring and Modeling the Needs and Preferences of Car Owners in Disadvantaged Communities

This research thrust is aimed at addressing research questions 3 and 4. We will combine surveys and interviews to improve our understanding of vehicle ownership in DACs to inform the potential for increasing PEV ownership in these communities. Given the diversity of the U.S. car buying population, we will focus on case studies of at least two locations, anticipated to be the Baltimore-Washington, D.C. region and the region around Denver, CO. These locations represent one large and one moderate sized metropolitan area and are conveniently accessible to the proposal team members. Final selection of the case study locations will be determined in consultation with DOE during award negotiation.

In each location, we will conduct interviews with (1) car buyers in DACs to obtain data on their needs and preferences with respect to vehicle ownership and operation, and (2) dealerships in and around DACs to obtain data on the types of financing opportunities available to buyers as well as data on the purchasing trends for low-income buyers, such as how frequently they buy versus lease vehicles, how often they shop for new versus used vehicles, etc. We will partner with used vehicle dealerships, such as CarMax, and post flyers at motor vehicle departments to obtain access to interviewees. The interviews will inform the design of surveys that we will field at dealerships as well as potentially online via panels such as those offered by Dynata, Qualtrics, etc. The surveys will contain both general questions about vehicle ownership conditions such as purchasing budgets, driving needs, and parking access as well as a series of choice-based conjoint questions that will quantify stated preferences for specific vehicle features, such as how much buyers in DACs are willing to pay for PEVs with different driving ranges and the

relative importance of external features, such as parking and charging access. This will supplement an upcoming survey of general car buyers this winter.

Preliminary Work: We have already converted the raw vehicle listings data described under the first research thrust into a structured database useful for analysis by compressing 406 large CSV files into partitioned parquet files in an Apache Arrow database. We have also begun several exploratory analyses to further understand summaries of the data. Preliminary summaries show states with ZEV mandates have higher percentages of PEVs listed while other states (such as North Dakota) are "PEV desserts" with nearly no PEVs available at dealerships. As foundational work for the second research thrust, we have conducted a pilot conjoint survey via a classroom project in a graduate course taught by Dr. Helveston. Results showed that factors specific to the used market, such as vehicle mileage, age, and warranties, are of high importance for used vehicle buyers. For used PEVs, the age and mileage of the vehicles are even more important than for used ICEVs as older cars with higher mileage tend to have a lower remaining driving range due to battery degradation.

Project Outcomes: The new data and insights about vehicle ownership and preferences of vehicle owners in DACs will help identify barriers to and solutions for increasing PEV adoption in these communities. The research will also benefit other modeling efforts regarding the dynamics of vehicle fleet turnover by unpacking when, where, and at what prices new and used vehicles are brought to dealerships at an unprecedented resolution. The estimated depreciation rates of most recent vehicles can also be used in multiple other projects, such as the "Total Cost of Ownership" (TCO) modeling at multiple national labs[1,4]. New data will be collected on state-level PEV incentives for every state at an annual basis between 2015-2023 and merged into the vehicle listings database. Spatial analyses of PEV supply over time will quantify the availability (both in terms of location and affordability) of PEVs in DACs. Finally, results will be integrated into NREL's EVI-Equity tool to reveal important equity implications of all analyses.

Project Outputs: The project will generate new analytical models and tools for understanding new and used market dynamics and their potential impacts on the equitable adoption of PEVs as well as new data and insights on the needs and preferences of vehicle owners in DACs. The data will hosted on https://livewire.energy.gov/.

Project Impacts: The assumptions about who will buy PEVs and how they will be used have consequences for the types of incentives and policies created to encourage PEV adoption; if those assumptions are inaccurate, we could end up perpetuating the biases that have existed to this point and failing to accelerate adoption in DACs. This project will benefit residents of DACs by improving our knowledge of vehicle owners' needs as well as the market dynamics that govern vehicle ownership in these communities.

Project Team and Qualifications: Dr. John Paul Helveston is an Assistant Professor of Engineering Management and Systems Engineering with expertise in survey design, choice modeling, qualitative interviewing, and techno-economic modeling of vehicle markets and technologies[5,6]. He also has expertise in data analysis and research software development in the R programming language and has authored multiple R packages for conjoint analysis[7,8]. Professor Helveston will serve as the primary project lead on all technical tasks, including survey design, interviews, and data analyses. He has a record of making his research findings accessible to broader audiences by writing press releases and policy briefings that condense his research for policy makers and other audiences[9,10]. The NREL collaborators include Dr. Dong-Yeon Lee, Eric Wood, and Jeff Gonder, who bring experience with charging infrastructure equity

metrics via the tool EVI-Equity, broader infrastructure analysis such as the extent of home charging access, and capabilities related to PEV market analysis[3,11]. The NREL team will facilitate interview and survey data collection for the Denver, CO case study as well as lead the effort on integrating the research findings into the EVI-Equity tool and making operational datasets generated through the project publicly available via Livewire.

2. PROJECT APPROACH

2.1. Problem

The Knowledge Gap: Electrifying the vehicle fleet is a cornerstone of most plans to curb the greenhouse gas emissions causing climate change, but plug-in electric vehicles (PEVs) are still not accessible for most U.S. car buyers. Policy interventions will be needed to make PEVs more accessible to disadvantaged communities (DACs), but little is known about the needs and preferences of these communities as well as the market dynamics governing the used vehicle market—where most people in DACs buy vehicles. By improving our understanding of the dynamics governing these markets, we will be able to design more effective and equitable policies and incentives to accelerate PEV adoption in DACs.

Current State: The current PEV adoption trend is an example of the "innovation-needs paradox," which suggests that the people that are likely to benefit the most from a new technology are often the last ones to adopt it[12]. Even with current government financial incentives, prices are still significantly higher for most *new* PEVs relative to comparable ICEVs[1], and buyers who lack dedicated parking at home or work for overnight charging may struggle to find a place to regularly charge. As a result, research has shown that as much as 90% of PEVs sold thus far in the U.S. have been purchased by wealthier buyers who typically have dedicated parking spots or garages[2]. But as more *new* PEVs are sold, *used* PEVs will become increasingly available. Research has shown that early PEVs have depreciated faster in the used market compared to ICEVs[13]. This dynamic could be critical for increasing PEV adoption in DACs.

Expected Change: This research will reveal new local knowledge about the needs and preferences of car owners in DACs as well as the role of the used market as a potential conduit for increasing PEV adoption in DACs. By improving our understanding of drivers' needs in DACs, we may be able to design more effective policies that address problems that are currently unknown, such as the significance of charging infrastructure access, vehicle features (e.g., price, range), and even dealerships in driving PEV adoption. Results will be specific to the two case study locations, though some outcomes may be more generalizable. For example, the integration of PEV supply mapping into the EVI-Equity tool will allow users to compare similar dynamics in cities across the U.S.

2.2. Project Approach

This overall approach of this project is to conduct two complementary research thrusts:

1. Quantifying key estimates of market dynamics related to PEV diffusion in the new and used markets by analyzing a large dataset of new and used vehicle listings.
2. Measuring and modeling the needs and preferences of car owners in DACs via interviews and surveys.

The research thrusts will be conducted in parallel, with initial *exploratory* tasks for each thrust being conducted in the first budget period and later *confirmatory* tasks for each thrust being conducted in the second budget period. This section describes each thrust in detail.

2.2.1. Research Thrust 1: Measuring and Modeling Market Dynamics for New and Used PEVs

For this research thrust, we will analyze a large data set of daily new and used vehicle listings to improve our understanding of important market dynamics between the new and used markets as well as how PEVs have been supplied to different communities over time. The used vehicle market is a critical yet understudied market. The vast majority of prior research on PEV adoption has focused on new PEVs, but the secondary market outpaces new vehicle sales by a factor of 2.4 to 1 and remains the only affordable source of vehicles for millions[14,15]. Furthermore, the average light-duty vehicle in the U.S. remains in the vehicle fleet for 17 years[16], with many remaining in use for 30 years or more (more-polluting light duty trucks in particular)[17]. As a result, many (if not most) lower-income buyers end up adopting older, dirtier vehicles compared to newer, cleaner (and more expensive) vehicles like PEVs.

The analyses conducted will generate key estimates of market characteristics and dynamics in the new and used markets, including (but not limited to) the following:

1. A spatial / temporal analysis of PEV supply in the new and used markets (e.g., where have automakers supplied the market as well as where vehicles go from the new to used markets?)
2. Estimates of the depreciation rates for every vehicle make and model over time, revealing how PEV affordability and residual value has changed and whether or not those changes are systematically different across different communities
3. The potential impact of different policies, such as PEV tax credits or state Zero Emission Vehicle (ZEV) mandates, on PEV supply or residual value.
4. The length of time every new and used vehicle make and model remains on different dealer lots as a proxy for underlying demand.
5. Spatial regressions of PEV supply over time to quantify the availability and prices of PEVs in close proximity to DACs.

Summary of the Data: The vehicle listings dataset to support this research thrust is sourced from marketcheck.com, a market research company that has collected data on vehicles available at nearly every dealership in North America from 2015 to the present—a period in which approximately 85% of all PEVs sold in the U.S. were listed. The listings data include daily data about when and where individual vehicles were listed for sale at dealerships as well as specifications about the vehicles, including the listing price, location, and thirty other detailed attributes, such as the make, model, trim, mileage, engine type, fuel type, color, etc. This dataset presents several unique advantages. First, it provides an unprecedentedly high-resolution lens into historical market outcomes with respect to PEVs competing with ICEVs in the new and used markets. And because each listing contains a unique VIN for each vehicle, individual vehicles can be tracked over time as they are bought and sold multiple times. The data can also reveal spatial diffusion patterns of PEVs supplied to different markets over time. The data were purchased by the PI at GWU under a license agreement that allows derivations of the raw data to be publicly shared. Thus, while the raw listings themselves cannot be made public, derived data sets from them can be used to support this research effort, including making those data sets publicly available.

Task 1.1: Spatial / Temporal Analysis of PEV Supply

The team will map out the historical supply of PEVs to the market at a high spatial (county) and time (monthly) resolution. This mapping will be comprehensive of nearly all vehicles supplied to

dealerships in the continental U.S. between 2015 and February 2023. Since the listings data contain unique Vehicle Identification Numbers (VINs) for each vehicle, individual vehicles can be tracked over time as they are sold in the new and then used market. This will enable a detailed view of any spatial or time trends in how PEVs have been adopted compared to ICEVs. Summary measures of PEV supply trends, such as the percentage of vehicles at every dealership that are PEVs over time, will help identify places where PEVs are supplied in abundance and places that are "PEV desserts" where virtual no PEVs are available. Figure 1 is an example summary chart showing the percentage of dealership listings that are PEVs by state and by month. The figure breaks states into categories as "ZEV" and "Non-ZEV" states. PEVs are clearly supplied more often in ZEV states, though some Non-ZEV states like Hawaii have experienced considerable supply. While Figure 1 is at the state-level, we anticipate conducting a much higher resolution mapping at the county or even zip code level to identify supply differences between DACs and non-DACs. We anticipate finding that PEVs have been prioritized in higher-income areas compared to the supply of otherwise similar ICEVs.

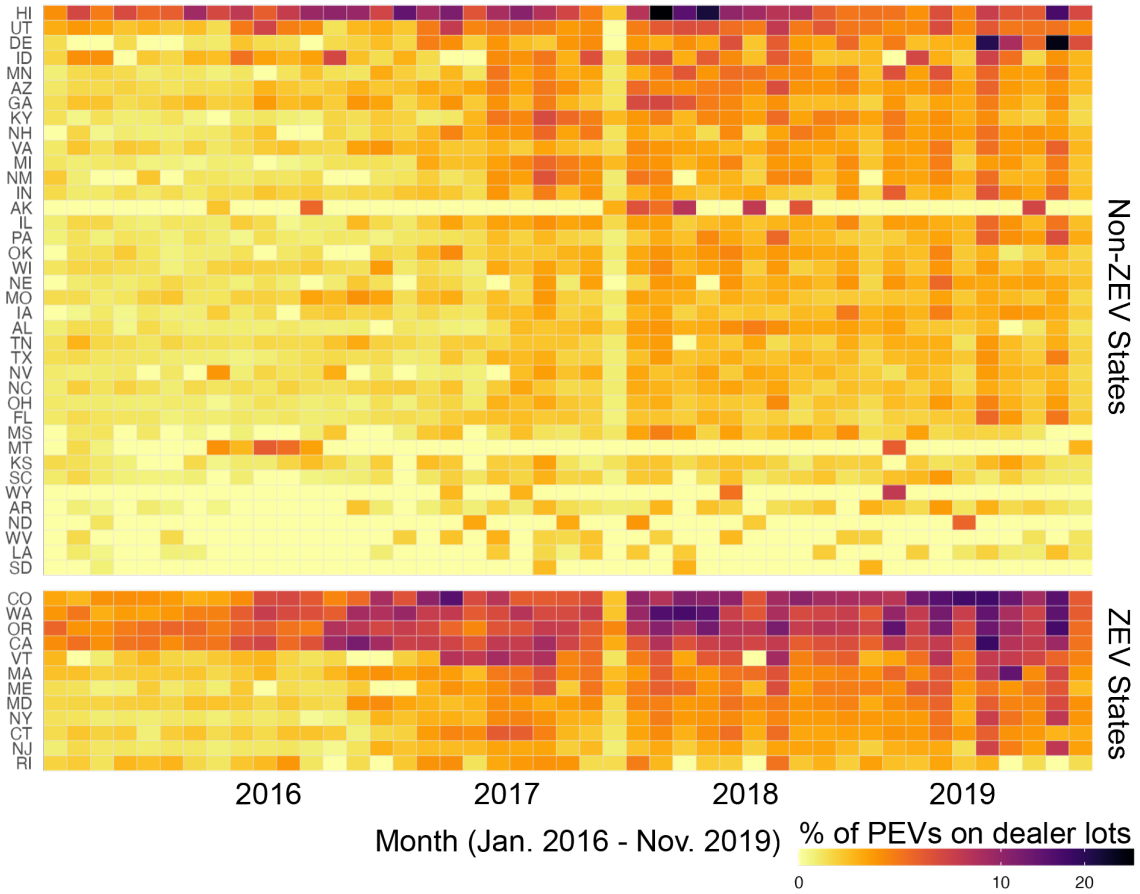

Fig. 1: Percentage of dealership listings that are PEVs by state and month.

Task 1.2: State-level PEV Incentive Data

The team will collect a new data set on state-level PEV incentives for every state at an annual basis between 2015-2023 and merge the data into the vehicle listings database. The team will leverage NREL staff who maintain the laws and incentives section of the Alternative Fuels Data Center, and will review state websites as well as existing literature as primary data sources[18].

These data will be critical for understanding how local-level policies may be affecting any spatial or time trends observed in the spatial mapping task. The data will also be used as important controls in several of the other tasks involving regressions.

Task 1.3: PEV Residual Value Analyses

The team will apply a series of regression analyses to quantify the residual value of every vehicle at the make and model level over time. These regressions will reveal answers to several important questions, including:

- Are PEVs depreciating in value faster or slower compared to similar ICEVs? How do results differ across different specific PEV makes and models?
- How have PEV depreciation rates changed over time (are they increasing, decreasing, or remaining constant)? How do results differ across different specific PEV makes and models?
- How have different policies, such as PEV tax credits or ZEV mandates, affected residual value for different PEVs?

As a starting point, ordinary linear regression will be used to regress vehicle final listing prices on age while controlling for other variables such as mileage, location, federal and state policies, gasoline prices, etc.

As with any regression analyses, we will apply multiple techniques to try and mitigate potential sources of bias. For example, introducing a lagged-dependent variable (LDV) term into some models that represents the new PEVs that were supplied in the previous time period can help address simultaneity since it operates under the assumption that future events do not influence past events. Such a model can be estimated by applying a generalized method of moments estimator and instrumenting with previous lags on different lags of the supply and using the J. Hansen statistic to test for over-specification[19]. Another approach is to use the number of days vehicles remain on dealership lots as a proxy for underlying demand; that is, all else being equal, vehicles that remain on the lot longer are likely in less demand than those that sell quickly. Finally, discrete events, such as the removal of Georgia's PEV purchase incentive 2015 or Colorado becoming a ZEV state in 2019, enable the potential for causal analyses via a difference-in-differences strategy.

Task 1.4: PEV Supply Equity Assessment

Given the high resolution of the listings data, the team will estimate spatial regressions of PEV supply over time to quantify the availability and prices of PEVs in and around DACs in the case study locations and compare them to other nearby locations. These regressions will reveal whether dealerships differentiate supply or price PEVs in / around DACs compared to non-DACs and whether any observed differences are unique to new or used markets. Results from these analyses will be compared with themes identified in the interview and survey results from the second research thrust. Robustness checks and sensitivity analyses will be conducted on all regressions to ensure that results are robust to model specification assumptions.

Once the regressions are complete, summary measures of interest such as the percentage of PEVs on dealership lots and relative PEV pricing will be integrated into the EVI-Equity tool developed by NREL. This integration will enable a novel look into the availability and affordability of new and used PEVs in different communities.

One example metric of interest with respect to equity is to compute the ratio of average PEV price to average household incomes for both new and used vehicles in different communities.

This could highlight PEV affordability in different locations and may reveal systemic inequalities in PEV availability.

2.2.2. Research Thrust 2: Measuring and Modeling the Needs and Preferences of Car Owners in Disadvantaged Communities

For this research thrust, we will use a combination of interviews and surveys to improve our understanding of vehicle ownership conditions in DACs to inform policies and incentives aimed at increasing PEV ownership in these communities. Given the broad diversity of the U.S. car buying population, we will focus on case studies of at least two locations, anticipated to be the Baltimore-Washington, D.C. region and the region around Denver, CO. These locations represent one large and one moderate sized metropolitan area and are conveniently accessible to the proposal team members. Final selection of the case study locations will be determined in consultation with DOE during award negotiation.

Task 2.1: Stakeholder Interviews

We will conduct interviews with personal vehicle buyers and dealership managers and employees in and around DACs in each case study location. Interviews with *vehicle buyers* will reveal new insights on the needs and preferences with respect to vehicle acquisition and operation in DACs. Interviews with *dealerships* will reveal information on the types of vehicles and financing opportunities available to buyers in DACs as well as information on their purchasing trends, such as how often they buy versus lease, how often they shop for new versus used vehicles, etc. Dealership interviews will also reveal other unknown potential barriers to PEV adoption in DACs, such as the extent to which dealerships promote PEVs to customers, how knowledgeable dealerships are about PEV incentives, etc. For example, an interview-based study from 2019 in Norway found that most dealerships interviewed actively directed customers to ICEVs over PEVs[20].

The team will develop semi-structured interview protocols for each target population (car buyers and dealerships). These protocols will be informed by multiple sources, including a review of prior literature on vehicle ownership and PEV adoption in DACs as well as initial exploratory interviews conducted prior to the formal start of the project.

The qualitative insights obtained from more open-ended ***interviews will be invaluable and critical for informing all other research tasks***. The specific questions included on surveys, for example, will be heavily influenced by the findings in these interviews. Interviews also provide one of the only research approaches for discovering otherwise unknown barriers to PEV adoption in DACs as they provide community stakeholders a voice to directly inform the research team of issues related to vehicle ownership and operation in their communities.

Sampling approach: Interviewees will be recruited by contacting dealerships such as CarMax via phone, email, and in person in each case study location to establish initial relationships and to explain the research goals and objectives. Short interviews with car buyers will be conducted at dealerships (with the permissions of the dealership) while they are waiting in the lobby or elsewhere on site, and longer follow-up interviews will be conducted either by phone or zoom with interviewees who opt in to conduct these interviews. Modest financial incentives will be provided for these longer follow-up interviews. Interviews with dealerships will follow a similar recruitment procedure, with initial shorter interviews followed by longer opt-in remote interviews or interviews at the dealership. Additional interviewees will be recruited via snowball sampling.

Analysis: The team will transcribe all interview data and draft memos on key themes and findings that emerge. These memos will summarize novel insights discovered about car buying needs and preferences in DACs as well as the roles that dealerships play in the process of acquiring a personal vehicle, including whether certain types of vehicles (e.g., ICEV vs. PEVS, new vs. used, etc.) are more heavily promoted over others and why.

Task 2.2: Vehicle Buyer Surveys

We will design and field surveys to quantify information about vehicle ownership and operation conditions in DACs in each case study location. The surveys will contain both general questions about vehicle ownership conditions as well as a series of choice-based conjoint questions for quantifying stated preferences for specific vehicle features. At a minimum, the general questions will capture data on the purchasing budgets, prior purchasing history, driving needs, and parking needs / access for vehicle buyers in DACs. The conjoint questions will enable quantification of vehicle buyers' preferences for general vehicle features (e.g., sensitivity to price, mileage, performance, etc.) as well as features specific to PEVs (e.g., sensitivity to driving range, charging access and speeds, etc.).

The collected data will enable us to compare the trends of consumer preferences in both new and used markets using multiple model specifications and techniques. While many previous studies have used similar techniques using conjoint survey data, this study will be the first to include both new and used vehicles and one of the first to specifically target vehicle buyers in DACs. In addition, this study will provide updated data from 2023 with vehicle attributes representative of the current and near future markets.

Sampling Approach: The surveys will be fielded using a combination of in person and online sampling to mitigate strengths and weaknesses of each fielding strategy. In person fielding provides the guarantee of obtaining samples from the target population, though sample sizes may be smaller. Online sampling provides a larger sample size but with less certainty over whether the online panel matches the desired target sample. We will work with an online panel provider, such as Dynata, Prolific, or Qualtrics, as they have been shown to have higher quality sampling compared to lower-cost providers such as Amazon Mechanical Turk[21]. Data collection will be monitored and verified throughout the collection process to ensure data quality meets expectations.

Modeling choice to quantify preferences: Conjoint surveys for choice modeling is a well-established statistical method for assessing consumer preferences across a wide variety of fields. One of the most common approaches for modeling choice is the maximum likelihood estimation of multinomial logit models[22], which is rooted in the theory of random utility models[23,24]. The central assumption of these models is that individual consumers make choices that maximize an underlying random utility model, which can be parameterized as a function of a product's observed attributes and a random variable representing the portion of utility unobservable to the modeler. These models produce estimates of the marginal utility for changes in each attribute relative to one another. These models can be used to estimate how much consumers are willing to pay for product features as well as predict consumer choices among sets of alternative products. Such models have been used widely to model consumer choice of automobiles, including prior studies by the PI [25–35].

Limitations: Conjoint surveys require relatively large sample sizes (e.g. 2,000 respondents per location) to produce precise estimates. As our focus is on car buyers in DACs, it may be challenging to obtain this sample size within each location. While online panels may help boost the sample size, coordinating with local partners such as dealerships, community outreach

centers, etc. will be important for reaching local residents. In addition, current market conditions are less typical than they have been historically due to supply constraints caused by the COVID-19 pandemic. Used vehicle prices, for example, are abnormally high, which could impact how respondents respond to interview or survey questions. Our results will have to be interpreted with this reality in mind.

2.3. Project Goal

Project Outcomes: This project will improve our knowledge about the needs and preferences of car owners in DACs as well as the role of the used market as a potential conduit for increasing PEV adoption in DACs. These outcomes will be measured by (1) statistical choice models from choice-based conjoint questions included on surveys, (2) theme encoding from qualitative interviews, (3) summary statistics of the vehicle listings data, and (4) multiple regressions of pricing and spatial supply of PEVs in the vehicle listings data. These outcomes will also benefit other modeling efforts regarding the dynamics of vehicle fleet turnover by unpacking when, where, and at what prices new and used vehicles are brought to dealerships at an unprecedented resolution. The estimated depreciation rates of most recent vehicles over the past seven years can also improve the accuracy of multiple existing projects, such as the TCO modeling at multiple national labs[1,4]. New data will be collected on state-level PEV incentives for every state at an annual basis between 2015-2023 and merged into the vehicle listings database. Spatial analyses of PEV supply over time will quantify the availability (both in terms of location and affordability) of PEVs in DACs. Results will be integrated into NREL's EVI-Equity tool to reveal important equity implications of all analyses.

Project Outputs: This project will develop new analytical models and tools for understanding new and used market dynamics and their potential impacts on the equitable adoption of PEVs in DACs. Specific outputs include:

- Spatial mappings of vehicle fleet turnover dynamics between the new & used markets.
- New estimates of depreciation rates for most recent vehicles over the past seven years.
- New annual state-level data on PEV incentives for every state between 2015-2023.
- Modeling results from spatial analyses of PEV supply over time quantifying the availability (both in terms of location and affordability) of PEVs in DACs.
- Extensions to the EVI-Equity tool that provide a novel lens into the availability and affordability of new and used PEVs in different communities.

The project will also generate new data sets on the needs and preferences of vehicle owners in DACs. This project will generate new knowledge in several critical areas for increasing PEV adoption in DACs:

- Knowledge about vehicle *acquisition* in DACs, such as vehicle purchase frequencies, budgets, propensity to buy or lease, propensity to purchase new versus used, etc.
- Knowledge about vehicle *operation* in DACs, such as parking availability, frequency of vehicle use, typical daily driving ranges, etc.
- Knowledge about currently unknown barriers to PEV adoption revealed by qualitative interviews.
- Knowledge about dynamics between the new and used vehicle markets, such as how different types of vehicles depreciate in value over time, whether PEVs are depreciating similarly to ICEVs, and effects of PEV policies on used market pricing and availability.
- Knowledge about how PEVs are being supplied to the market and whether they are being equitably supplied or priced in different communities.

Project Innovativeness and Replicability: The innovative nature of this project is rooted in combining rigorous qualitative and quantitative methods. The qualitative work will reveal previously unknown insights into barriers to PEV adoption in DACs, and the quantitative work will generate new knowledge about important market dynamics between the new and used vehicle markets, a heavily understudied area.

Furthermore, while most studies on technology adoption focus on demand-side measures (e.g., surveys of buyers, sales data, etc.), this research takes an innovative approach to combine novel data on both vehicle demand (preference modeling) and supply (vehicle listings data). The vehicle listings data also provide an unprecedentedly high spatial and temporal resolution of vehicle supply to the market over a critical time period. These data alone are highly valuable for understanding market dynamics; combined with interviews and conjoint surveys, the overall project is highly innovative in both methods and the resolution of outcomes. Finally, integrating these insights into an improved version of NREL's EVI-Equity tool will reveal important equity implications of all analyses and make them more accessible to the public and other researchers.

This research will also serve as an example that can be replicated in other communities and in other contexts. For example, electrifying heavy-duty vehicles and long-distance shipping is an important goal for decarbonizing our transportation systems. Studying interactions between the new and used market in these domains can help identify limits to fleet turnover, and combining these results with qualitative interviews and surveys could reveal similarly novel insights about unique barriers to electrification in these domains.

2.4. Justice 40 Considerations

Historically, people with disabilities, low-income communities, and communities of color have experienced greater exposure to air pollution from passenger vehicles compared to those in more affluent communities[36,37], leading to differential health outcomes[38]. PEVs promise the opportunity to substantially reduce local air pollution from tailpipe emissions, but they have been primarily adopted in relatively wealthy communities[2,39].

This project aims to discover previously unknown barriers to PEV adoption by improving our understanding of the needs and preferences of car owners in DACs as well as the role of the used market as a potential conduit for increasing PEV adoption in DACs. By improving our understanding of drivers' needs in DACs, we may be able to design more effective policies that address currently unknown problems, such as the significance of charging infrastructure access, vehicle features (e.g., price, range), and even the role that dealerships play in accelerating (or restricting) PEV adoption.

In addition, the improvements made to the EVI-Equity tool will help inform decision makers with respect to PEV policies and infrastructure planning that would promote greater PEV adoption in DACs. This will provide decision makers with a new equity lens through which they can judge the potential equity implications of future planning.

3. Market Transformation Plan

Several barriers to greater PEV adoption are well-known: higher initial purchase prices, limited driving ranges, and limited charging infrastructure. But these may not be the only barriers (or even the most important barriers) to greater PEV adoption in DACs. Crafting long-term policy solutions to increase PEV adoption in DACs requires first understanding what the most critical barriers are.

For this reason, one of the most significant long-term benefits of this research is that it provides car owners in DACs an opportunity to voice their needs and preferences to the research team via interviews and surveys at a time when PEV adoption in these communities is still low. By providing this opportunity now, we expect that the insights obtained from interviews and surveys of car buyers and dealers in DACs will have long-lasting impacts by revealing previously unknown barriers to greater PEV adoption in DACs.

In addition, this project will generate a substantial amount of data that will be made publicly accessible. As noted, we will post all data from the project on the Livewire Data Platform, which NREL leads in collaboration with PNNL and INL. These data include:

- Structured summary data from the vehicle listings data on vehicle pricing, mileage, availability, turnover dynamics, etc. Raw listings data cannot be made public as they contain identifiable information, but summaries and data anonymized for analysis will be made public.
- Spatial mappings of vehicle fleet turnover dynamics between the new and used markets for ICEVs, PEVs, and hybrid vehicles and other visualizations of vehicle diffusion trends over time.
- New longitudinal (i.e., through time) state-level data on PEV incentives for every state at an annual basis between 2015-2023.
- New interview data and qualitative insights in DACs about (1) vehicle acquisition, (2) vehicle operation, (3) specific barriers to PEV adoption, and (4) the role dealerships play in vehicle acquisition (in general and PEV adoption specifically). NREL's experience hosting survey data the Transportation Secure Data Center (TSDC)[40,41], which falls under the Livewire umbrella, will be leveraged to ensure appropriate management of any Personally Identifiable Information (PII) from survey participants.
- An updated version of NREL's EVI-Equity tool that integrates all robust results from this research, revealing important equity implications of all analyses.
- New survey data of car buyers in DACs, including general survey data on vehicle acquisition and operation conditions as well as choice-based conjoint questions on car buying preferences (again, leveraging the team's experience to appropriately handle any PII collected as part of the survey process).

The research will also have longer-term and broader benefits from supporting other modeling efforts regarding the dynamics of vehicle fleet turnover. The estimated depreciation rates of most recent vehicles, for example, can also improve the accuracy of multiple existing projects, such as the TCO modeling at multiple national labs[1,4].

4. WORKPLAN

4.1. Project Summary by Budget Period

The project will be conducted in two budget periods, with initial *exploratory* tasks for each research thrust being conducted in the first budget period and later *confirmatory* tasks for each thrust being conducted in the second budget period.

Budget Period 1: *Exploratory* Market Dynamics in DACs

Summary:

The recipient will conduct initial exploratory analyses with the large dataset of new and used vehicle listings to begin mapping spatial and temporal trends in the supply of new and used PEVs to different areas, including DACs. Explorations will include investigating when, where, and at what prices both new and used vehicles of different powertrain are supplied to the market, specifically looking for trends in PEV diffusion over time and technology diffusion from the new to used market. New longitudinal state-level data on PEV incentives will also be compiled along with other important data (e.g., fuel prices, demographics, etc.) to be used in analyses during budget period 2.

This analysis will coincide with car buyers and dealership interviews in DACs in two case study locations to obtain a more general understanding of car buyers' needs and preferences with respect to vehicle ownership and operation. Interviews will inform initial pilot surveys that will be designed and tested in preparation for final surveys to be fielded in budget period 2. Results from both tasks will reveal qualitative insights about vehicle ownership in general and barriers to increasing PEV ownership specifically in DACs.

Expected Outcomes:

- Publicly accessible data sets of vehicle listings and fleet turnover dynamics. Raw listings data cannot be made public as they contain identifiable information, but summaries and data anonymized for analysis will be made public.
- Spatial mappings of vehicle fleet turnover dynamics between the new and used markets for ICEVs, PEVs, and hybrid vehicles.
- Visualizations of vehicle diffusion trends over time.
- New longitudinal data on PEV incentives for every state at an annual basis between 2015-2023.
- New interview data and qualitative insights in DACs about (1) vehicle acquisition, (2) vehicle operation, (3) specific barriers to PEV adoption, and (4) the role dealerships play in vehicle acquisition (in general and PEV adoption specifically).
- Initial pilot survey designs based on insights from the interviews and prior research.
- Estimates of required sample sizes for the final survey.

Budget Period 2: *Confirmatory* Market Dynamics in DACs

Summary:

The recipient will analyze detailed historical vehicle listings data to obtain key estimates of important market characteristics and dynamics, including the supply of new and used vehicles to the market (with a focus on PEVs supply to DACs), the depreciation rates of every vehicle make and model, the potential impact of different incentives such as tax credits on PEV residual value, and vehicle inventory timing as a proxy for PEV demand. Results will be integrated into the EVI-Equity tool developed by NREL to assess PEV availability in different communities (both in terms of location and affordability).

The recipient will also design and field conjoint surveys to quantify information about vehicle ownership for car owners in DACs, including purchasing budgets, driving needs, vehicle preferences, and parking access. These data will reveal stated preferences in DACs from the two case study regions for vehicles in general as well as features specific to PEVs, such as driving range.

Expected Outcomes:

- New estimates for the depreciation rates of most recent vehicles over the past seven years.
- Results from spatial analyses for PEV supply over time quantifying the availability (both in terms of location and affordability) of PEVs in DACs.
- Updated version of NREL's EVI-Equity tool that integrates all robust results from this research, revealing important equity implications of all analyses.
- New data and insights about vehicle ownership and preferences of vehicle owners in DACs to help identify barriers to and solutions for increasing PEV adoption in these communities.
- New choice models for predicting vehicle choice among vehicle buyers in DACs.

4.2. Project Schedule

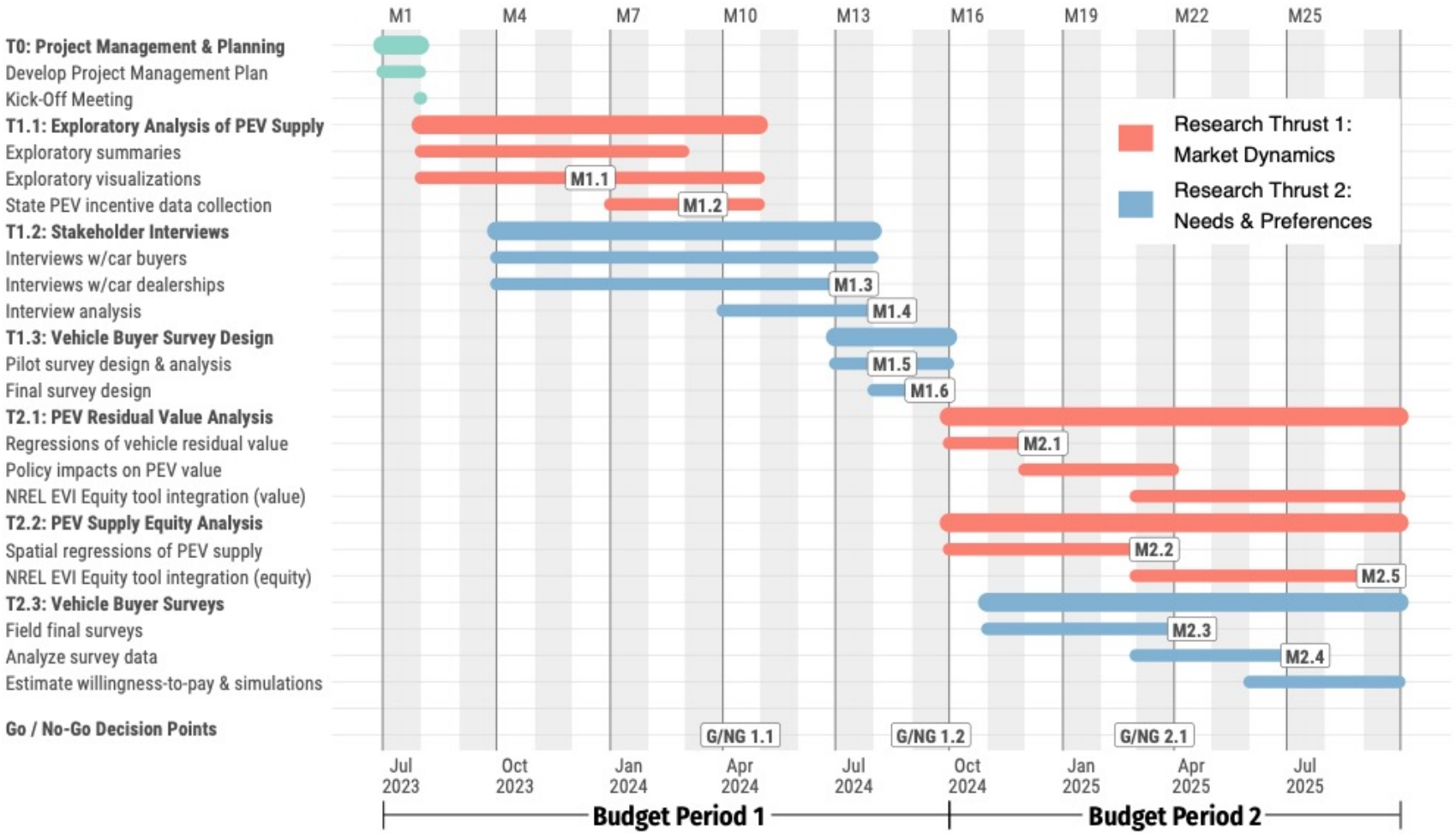

Fig. 2: Gantt chart of project schedule.
Colors indicate research thrusts (red = 1, blue = 2).
M = Milestones, G/NG = Go / No Go Points.

4.3. Work Breakdown Structure (WBS)

Team members in the WBS are denoted as follows:

- JPH = Dr. John Paul Helveston
- DYL = Dr. Dong-Yeon Lee
- JG = Jeff Gonder

Task 0.0 – Project Management and Planning

The Recipient shall develop and maintain the Project Management Plan (PMP). The content, organization, and requirements for revision of the PMP are identified in the Federal Assistance Reporting Checklist and Instructions. The Recipient shall manage and implement the project in accordance with the PMP.

Task 0.1 – Kick-Off Meeting

The Recipient will participate in a project kickoff meeting with the DOE within 30 days of project initiation.

Budget Period 1: *Exploratory* Market Dynamics in DACs

Task 1.1 – Exploratory Analysis of PEV Supply

Location(s) and Task Leads: Baltimore-Washington (JPH)

Subtask 1.1.1 (JPH) – The recipient will use new and used vehicle listings data to examine the historical supply of PEVs to the market at a high spatial (county) and time (monthly) resolution. This mapping will be comprehensive of nearly all vehicles supplied to dealerships in the continental U.S. between 2015 and 2023. The mappings will reveal spatial and time trends as well as trends in the movement of vehicles from the new to used markets. Analysis will include computing summary measures of PEV supply trends, such as the percentage of vehicles at every dealership that are PEVs over time to help identify places where PEVs are supplied in abundance and places that are "PEV desserts." Individual vehicles can be tracked over time as the listings data contain unique Vehicle Identification Numbers (VINs).

Subtask 1.1.2 (JPH) – The recipient will create summary visualizations of supply trends over time, including static and interactive charts (e.g., R Shiny applications). Visualizations will aid in the discovery of supply trends as well as provide a tool for communicating findings. Analyses will be particularly focused on identifying differences in the supply of PEVs in comparison to ICEVs in different communities.

Subtask 1.1.3 (JPH & DYL) – The recipient will generate a new longitudinal dataset on state-level PEV incentives for every state at an annual basis between 2015-2023 and merge this into the vehicle listings database. These data will be used in the next budget period, though results may also help build hypotheses for identified spatial trends. Additional data on demographics will also be collected.

Task 1.2 – Stakeholder Interviews

Location(s) and Task Leads: Baltimore-Washington (JPH); Denver (DYL)

Subtask 1.2.1 (JPH & DYL) – The recipient will conduct interviews with *car buyers* in DACs in each case study location to obtain data on their needs and preferences with respect to vehicle ownership and operation. Interviews will also inform the design of surveys fielded in the in the next budget period. An initial recruitment strategy is to partner with large used vehicle dealerships such as CarMax to obtain access to this population of buyers. Secondary approaches include posting recruitment flyers at local motor vehicle departments. The team anticipates interviewing at least 10 - 20 buyers in each study location, though the final number may be larger to ensure identification of key themes.

Subtask 1.2.2 (JPH & DYL) – The recipient will conduct interviews with *dealerships* in and around DACs in each case study location to obtain data on the types of financing opportunities available to low-income buyers (as a proxy for buyers in DACs) and PEV buyers as well as data on the purchasing trends for low-income buyers, such as how frequently they buy versus lease vehicles, how often they shop for new versus used vehicles, etc. The team anticipates conducting at least 10 - 20 car dealer interviews in each study location, though the final number may be larger to ensure identification of key themes.

Subtask 1.2.3 (JPH & DYL) – For recorded interviews, the recipient will transcribe the interviews verbatim for analysis. The recipient will review notes and transcripts and write memos on central themes and findings. These memos will inform the design of the pilot surveys in the next task as well as provide new information about other important conditions affecting PEV adoption in DACs.

Task 1.3 – Vehicle Buyer Survey Design

Location(s) and Task Leads: Baltimore-Washington (JPH); Denver (JG)

Subtask 1.3.1 (JPH & JG) – The recipient will design a pilot survey based on interview data and prior research. This pilot survey will primarily be used to test the desired survey functionality and complete initial power assessments to identify the specific required sample size for the final survey, which will be fielded in budget period 2.

Subtask 1.3.2 (JPH & JG) – The recipient will design a final survey based on analyses of the pilot survey results. The survey will include both general questions about vehicle ownership conditions, such as purchasing budgets, driving needs, and parking access, as well as a series of choice-based conjoint questions that will quantify stated preferences for specific vehicle features, such as how much buyers in DACs are willing to pay for PEVs with different driving ranges and the relative importance of external features, such as parking and charging access. The survey will be fielded in budget period 2.

Budget Period 2: Confirmatory Market Dynamics in DACs

Task 2.1 – PEV Residual Value Analysis

Location(s) and Task Leads: Baltimore-Washington (JPH); Denver (DYL)

Subtask 2.1.1 (JPH) – The recipient will use used vehicle listings data to quantify the residual value of every vehicle at the make and model level over time. Ordinary linear regression will be used to regress vehicle final listing prices on age while controlling for other variables such as mileage.

Subtask 2.1.2 (JPH) – The recipient will integrate the PEV incentive data and the used vehicle listings data to quantify the potential impact of different incentives such as tax credits on PEV residual value. Additional regressions will quantify whether incentives for *new* PEVs have had a lasting effect on the residual value of those vehicles in the *used* market. For example, since subsidies reduce the *new* purchase price, *used* prices may remain suppressed (otherwise buyers would buy new and get the subsidy). Discrete events, such as the removal of Georgia's PEV purchase incentive in 2015, enable the potential for a causal analysis.

Subtask 2.1.3 (DYL) – The recipient will integrate the updated vehicle residual value analyses into the NREL EVI-Equity tool to improve the precision of its PEV affordability estimates.

Task 2.2 – PEV Supply Equity Analysis

Location(s) and Task Leads: Baltimore-Washington (JPH); Denver (DYL)

Subtask 2.2.1 (JPH) – The recipient will use used vehicle listings data to conduct spatial regressions of PEV supply over time to quantify the availability and prices of PEVs in close proximity to DACs in the case study locations and compare them to other locations. The state-level policy data collected in the previous budget period will be used to assess whether the supply of PEVs has been prioritized to states or sub-state regions to meet policy requirements, such as states with Zero Emission Vehicle (ZEV) mandates that require automakers to sell PEVs in those states.

Subtask 2.2.2 (DYL) – The recipient will integrate the findings from the previous subtask into the NREL EVI-Equity tool to assess how PEV availability has changed in different communities over time. Distance to nearest dealership with PEVs available will be one potentially added metric in this regard.

Task 2.3 – Vehicle Buyer Surveys

Location(s) and Task Leads: Baltimore-Washington (JPH); Denver (JG)

Subtask 2.3.1 (JPH & JG) – The recipient will field the surveys designed in the previous budget period at dealerships as well as potentially online via panels such as those offered by Dynata, Prolific, and Qualtrics. Recruitment flyers posted at local motor vehicle departments is an additional recruitment strategy. Data collection will be monitored and verified throughout the collection process to ensure data quality meets expectations (e.g., filtering out random responses, bots, speeding through the survey, etc.). The sample will be targeted to the two case study locations in this project.

Subtask 2.3.2 (JPH) – The recipient will analyze the survey data. Analysis will include summary measures of the sample population; summary measures of key metrics such as purchasing

budgets, driving needs, and parking access; and estimation of discrete choice models to quantify stated preferences for vehicle features.

Subtask 2.3.3 (JPH & DYL) – The recipient will estimate consumer willingness to pay (WTP) for vehicle features as well as conduct simulations to assess willingness to adopt different vehicles, with an emphasis on assessing key features for increasing willingness to adopt a PEV as well as the significance of buying new versus used vehicles.

4.4. Summary of Milestones and Go / No-Go Decision Points

BUDGET PERIOD 1 (07/01/2023 - 09/30/2024)

Milestone 1.1 *Exploratory Analysis of PEV Supply (12/2023)*

Associated task(s):	1.1 – Spatial / Temporal Analysis of PEV Supply
Description:	Visualizations of PEV supply over time created, including fleet turnover dynamics between the new and used markets for ICEVs, PEVs, and hybrid vehicles. Key trends in PEV supply over time are identified and quantified, including how the percentage of PEVs available at dealerships has changed spatially and over time.
Verification:	Slides provided to DOE showing the visualizations.

Milestone 1.2 *Data Processing (03/2024)*

Associated task(s):	1.1 – Spatial / Temporal Analysis of PEV Supply
Description:	Completed collection and integration of state-level PEV incentive data from 2015-2023 into vehicle listings data. Data sets of vehicle listings and fleet turnover dynamics are formatted, cleaned, de-identified, and provided to Livewire to be made publicly available.
Verification:	DOE project manager copied on the email correspondence providing the data to the Livewire team.

Go/No-Go 1.1 *Spatial Exploratory Analysis Completion (04/2024)*

Associated task(s):	Task 1.1 – Spatial / Temporal Analysis of PEV Supply
Description:	Exploratory summaries and visualizations of the vehicle listings data must reveal spatial and time trends in PEV supply and trends in the movement of vehicles from the new to used markets. If no new insights are obtained from the exploratory analyses, it will be difficult (if not impossible) to estimate informed spatial regressions in future tasks.
Evaluation	Visualizations and data summaries should reveal clear trends in (1) the supply of PEVs (in comparison to ICEVs) over space and time, and (2)

Criteria:	trends in how vehicles move from the new to used market. These results will be represented both in visual summaries through charts as well as numeric summaries, e.g., percentages of vehicles at dealerships that are PEVs vs. ICEVs.

Milestone 1.3 *Interviews (07/2024)*

Associated task(s):	1.2 – Stakeholder Interviews
Description:	Interviews with car buyers and dealerships complete and all interviews are verbatim transcribed for analysis.
Verification:	Statistics regarding the conducted interviews shared with the DOE project manager in a document or slide presentation.

Milestone 1.4 *Interview Analyses (08/2024)*

Associated task(s):	1.2 – Stakeholder Interviews
Description:	All transcribed interviews are coded and analyzed to identify key themes and findings. Memos on central themes and findings from interviews are written to identify qualitative insights on barriers to PEV adoption and to support survey development.
Verification:	Developed memos shared with the DOE project manager.

Milestone 1.5 *Pilot Survey Design and Analysis (08/2024)*

Associated task(s):	Task 1.3 – Vehicle Buyer Survey Design
Description:	Pilot survey designs are completed and fielded. Power analyses are conducted to assess the required sample sizes for the final survey. Analysis of pilot data complete to inform final survey designs.
Verification:	Outcomes of analysis shared with DOE project manager in a slide presentation.

Milestone 1.6 *Final Survey Design (09/2024)*

Associated task(s):	Task 1.3 – Vehicle Buyer Survey Design
Description:	Design of final surveys complete, informed by insights from pilot survey.
Verification:	Final survey design details shared with DOE project manager.

Go/No-Go 1.2 *Interview Completion (09/2024)*

Associated task(s):	1.2 – Stakeholder Interviews
Description:	While there is no fixed number of interviews that can be pre-determined as sufficient to conclude the interview task, the team expects to conduct at least 10 - 20 interviews in each study location. Without key themes or new insights identified, the survey design would be suboptimal and less informed.
Evaluation Criteria:	Interview data will be continuously processed until central themes emerge and are identifiable. Direct quotes from interviews will be used to identify themes and memos will be written to summarize results.

BUDGET PERIOD 2 (10/01/2024 - 09/30/2025)

Milestone 2.1 *PEV Residual Value Analysis (12/2024)*

Associated task(s):	Task 2.1 – PEV Residual Value Analysis
Description:	Initial regressions of vehicle value and depreciation rates over time complete for every vehicle make and model, including potential effects of PEV incentives on residual value.
Verification:	Details of residual value analysis submitted to the DOE project manager as a slide deck or a draft research paper.

Milestone 2.2 *PEV Supply Equity Analysis (03/2025)*

Associated task(s):	Task 2.2 – PEV Supply Equity Analysis
Description:	Regressions to assess equitable supply of PEVs over time to different communities complete, quantifying the availability (both in terms of location and affordability) of PEVs in DACs.
Verification:	Details of PEV supply equity analysis submitted to the DOE project manager as a slide deck or a draft research paper.

Go/No-Go 2.1 *Regression Analysis Completion (03/2025)*

Associated task(s):	Task 2.1 – PEV Residual Value Analysis Task 2.2 – PEV Supply Equity Analysis
Description:	Residual value analyses results and spatial regression results must be statistically significant, and significance and effect sizes should be robust to variations in model specifications. If results are insufficiently significant or robust, they cannot be reliably integrated into the EVI-Equity Tool.
Evaluation Criteria:	Key coefficients in regression results should be statistically significant according to statistical hypothesis testing at the 95% confidence level, and

	significance (and effect sizes) should be robust to variations in model specifications.

Milestone 2.3 *Survey Data Collection (04/2025)*

Associated task(s):	Task 2.3 – Vehicle Buyer Surveys
Description:	All final surveys fielded and data is collected and verified to meet quality expectations in terms of capturing the population of interest.
Verification:	Statistics regarding the conducted surveys shared with the DOE project manager in a document or slide presentation.

Milestone 2.4 *Survey Data Analysis (07/2025)*

Associated task(s):	Task 2.3 – Vehicle Buyer Surveys
Description:	Survey data are analyzed. Choice models are estimated and quantification of vehicle buyer preferences are complete. Assessments of WTP and simulations of PEV adoption under different conditions are conducted.
Verification:	Summary of the analyses and modeling submitted to the DOE project manager as a slide deck or a draft research paper.

Milestone 2.5 *Integration Into EVI-Equity Tool (09/2025)*

Associated task(s):	Task 2.1 – PEV Residual Value Analysis; Task 2.2 – PEV Supply Equity Analysis
Description:	New vehicle depreciation results and supply equity results are integrated into the NREL EVI-Equity tool, providing improved estimates of PEV affordability and availability.
Verification:	Slides submitted to DOE project manager demonstrating enhancements integrated into EVI-Equity.

4.5. End of Project Goal

One major goal is to generate new knowledge about the needs and preferences of car owners in DACs as well as the role of the used market as a potential conduit for increasing PEV adoption in DACs. These outcomes will be measured by (1) multiple regressions of pricing and spatial supply of PEVs in the vehicle listings data, (2) summary statistics of the vehicle listings data, (3) statistical choice models from choice-based conjoint questions included on surveys, and (4) theme encoding from qualitative interviews.

Another goal is to benefit modeling efforts regarding the dynamics of vehicle fleet turnover by unpacking when, where, and at what prices new and used vehicles are brought to dealerships at an unprecedented resolution. The estimated depreciation rates of most recent vehicles over

the past seven years can also improve the accuracy of multiple existing projects, such as the TCO modeling at multiple national labs[1,4]. New longitudinal data will be collected on state-level PEV incentives for every state at an annual basis between 2015-2023 and merged into the vehicle listings database. Spatial analyses of PEV supply over time will quantify the availability (both in terms of location and affordability) of PEVs in DACs. Results will be integrated into NREL's EVI-Equity tool to reveal important equity implications of all analyses.

The project will generate new analytical models and tools for understanding new and used market dynamics and their potential impacts on the equitable adoption of PEVs in DACs. This includes spatial mappings revealing new information about adoption trends and turnover rates between the new and used markets as well as new estimates for the depreciation rates of most recent vehicles over the past seven years. Analytical models of spatial analyses will show how PEVs have been supplied to the market over time, focusing on availability and affordability in DACs. These results will also be incorporated into the EVI-Equity tool.

The project will also generate new data sets and insights on the needs and preferences of vehicle owners in DACs. This project will generate new knowledge in several critical areas for increasing PEV adoption in DACs, including new knowledge about:

- Vehicle *acquisition* in DACs, such as vehicle purchase frequencies, budgets, propensity to buy or lease, propensity to purchase new versus used, etc.
- Vehicle *operation* in DACs, such as parking availability, frequency of vehicle use, typical daily driving ranges, etc.
- Currently unknown barriers to PEV adoption revealed by qualitative interviews.
- Important dynamics between the new and used vehicle markets, such as how different types of vehicles depreciate in value over time, whether PEVs are depreciating similarly to ICEVs, and effects of PEV policies on used market pricing and availability.
- How PEVs are being supplied to the market and whether they are being equitably supplied and/or priced in different communities.

4.6. Project data

The project will generate the following data:

- Structured summary data from the vehicle listings data on attributes such as vehicle pricing, mileage, availability, and turnover dynamics. Raw listings data cannot be made public as they contain identifiable information, but summaries and data anonymized for analysis will be made public.
- Spatial mappings of vehicle fleet turnover dynamics between the new and used markets for ICEVs, PEVs, and hybrid vehicles and other visualizations of vehicle diffusion trends over time.
- New longitudinal state-level data on PEV incentives for every state at an annual basis between 2015-2023.
- New interview data and qualitative insights in DACs about (1) vehicle acquisition, (2) vehicle operation, (3) specific barriers to PEV adoption, and (4) the role dealerships play in vehicle acquisition (in general and for PEV adoption specifically).
- An updated version of NREL's EVI-Equity tool that integrates all robust results from this research, revealing important equity implications of all analyses.

- New survey data of car buyers in DACs, including general survey data on vehicle acquisition and operation conditions as well as choice-based conjoint questions on car buying preferences for new and used vehicles and PEVs.

4.7. Project Management and Controls

At the start of the project, all planned project tasks along with their initial expected timelines will be added onto a team project task management system, likely to be Trello (or a similar software). The project PI will lead in the creation of this task management system. All team members will be able to view and edit the task planner, and the planner will serve as a high-level guideline to keep individual tasks organized and on schedule.

Throughout the project, all team members will join on a quarterly call via Zoom to discuss the status / progress of current tasks, whether any milestones in the previous quarter were achieved, and next steps on the tasks in the following quarter. If a go / no-go decision point was reached in the latest quarter, the PI will review the status of the tasks related to the go / no-go decision to determine whether necessary progress has been made to continue forward with the project. Discussion between relevant parties for smaller sub-tasks will be held as needed via a dedicated Slack workspace to facilitate more immediate and streamlined communication. Email and zoom calls will also be used. Changes to individual tasks will be discussed with the PI directly before being approved.

Salary, fringe, and tuition expenses will be managed by the PI's institutional office of sponsored research (GWU). Other expenses will be management through reimbursement via Concur software, also through GWU. Expenses must be submitted within 60 days of incurred costs to be properly reimbursed via GWU.

Risk management is an important aspect of the proposed research. For the tasks related to market dynamics using the vehicle listings data, simulation will be an important risk mitigation strategy. More specifically, estimated models will be used to simulate data and compared against the data used to estimate the model. Misalignment between true and simulated data is a good indicator of potential errors in programming or modeling. For the interview and survey tasks, one major risk is the potential for lost data (e.g. interview recordings / transcriptions or survey responses). This risk will be mitigated by using the GWU Box backup system to keep a master copy of all data. In addition, a backed-up dictionary file will be used to separate identifiable information (e.g. about interviewees) from their interview responses. This adds an additional layer of protection between the data and any identifiable information.

5. Project Team and Qualifications

This project is a partnership between the George Washington University (GWU) and the National Renewable Energy Lab (NREL). Professor Helveston (GWU) will serve as the primary project lead on all technical tasks, including survey design, interviews, and data analyses. The NREL team, consisting of Dr. Dong-Yeon Lee, Eric Wood, and Jeff Gonder, will facilitate interview and survey data collection for the Denver, CO case study as well as lead the effort on integrating the research findings into the EVI-Equity tool.

Our team is well-situated to execute this research and to successfully disseminate the findings in an impactful way. PI Helveston is known for his expertise in multiple data collection and analysis methods (including quantitative and qualitative methods) as well as his expertise in PEV technology, markets, and policies in the U.S. and in China. NREL is an ideal FFRDC partner for this project. With decades of leadership in clean energy research, development, and

deployment, NREL possesses a wealth of expertise knowledge that is forming the foundation of the clean energy transition. Their mission is to lead an energy transition to a clean energy future in which solutions are inclusively designed and benefits are equitably distributed. NREL is a leader in applied clean energy practices, and thousands of communities around the world have benefited from their research, including many that are historically underserved in terms of access to clean energy or its benefits. This research continues that legacy by searching for new knowledge to promote clean energy vehicle adoption in DACs.

Team member summary

Dr. John Paul Helveston is an Assistant Professor of Engineering Management and Systems Engineering with expertise in survey design, choice modeling, qualitative interviewing techniques, and techno-economic modeling of vehicle markets and technologies[5,6]. He also has expertise in data analysis and research software development in the R programming language and has authored multiple R packages for conjoint analysis[7,8]. He also has a history of working with a diverse research team and mentoring diverse students, and he will continue to include and recruit underrepresented minorities (URM) and women in STEM in this project. Of the coauthors with whom he has published articles (including his own Ph.D. students), 57% are women and 34% are URMs. He is currently working on various research projects with three doctoral students (two women and one URM), one masters student (a URM), and four undergraduates students (all women). In addition to his publications in peer-reviewed journals, Professor Helveston has a record of making his research findings accessible to broader audiences by writing press releases and policy briefings that condense his research for policy makers and other audiences[9,10]. He is a firm supporter of open source research and teaching, and he has made all of his research and teaching materials open source available at https://github.com/jhelvy/.

Jeff Gonder will oversee and coordinate NREL's work on the project. Mr. Gonder leads the Mobility, Behavior and Advanced Powertrains Group within NREL's Center for Integrated Mobility Sciences (CIMS), where he supervises over two dozen researchers on mobility and energy topics including travel behavior and modeling/simulation of advanced vehicle design, market penetration, and GHG emissions. Gonder has additionally led numerous successful research projects ranging from relatively small efforts under a year in duration to larger multi-year and multi-million-dollar research initiatives. His project leadership experience includes multiple efforts funded by the VTO Analysis program, and familiarity with numerous transportation surveys and studies involving recruitment of volunteer participants through managing the Transportation Secure Data Center which he founded a dozen or so years ago[40,41]. Gonder additionally contributes to the Livewire Data Platform, in which the team will make data generated through the course of the project publicly available. In addition to general oversight of NREL's contributions and data resources, Gonder will support survey design efforts in the project, will oversee the planned survey deployments in the Denver area, and will interface with the Alternative Fuels Data Center laws and incentives team for help assembling the longitudinal electrified vehicle policies and incentives dataset for the project. Gonder has sufficient availability over the planned duration of the project to devote the time allocated for completing these tasks.

Dr. Dong-Yeon Lee leads development of the EVI-Equity model at NREL[3]. His roles on the project will include conducting technical analysis, supporting integration of the vehicle market and consumer behavior data collected throughout the project into EVI-Equity, and generating equity metrics (such as improved access to electric vehicles and chargers, affordability of new and/or used electric vehicles, decarbonization-for-all potential, capabilities justice, and human

health). Lee leads various other projects related to environmental justice and energy equity, including the refinement and expansion of EVI-Equity, as well as LA100 – Equity Strategies (which has the goal of achieving equitable transitions toward 100% renewable energy use in the city of Los Angeles in the next few decades). Lee additionally leads a task in an ongoing multi-lab consortium (JUST – Joint office United Support for Transportation electrification) for the Joint Office of Energy and Transportation. Lee's deep involvement in the EVI-Equity model will ensure successful integration of the proposed data collected and generated through this project into EVI-Equity and corresponding analysis of broader equity implications. Lee's knowledge and experience on equitable energy systems will also help steward the overall project in the right direction. Lee has sufficient availability over the planned duration of the project to devote the time allocated for completing the proposed tasks, including data collection, integration, and analysis.

Eric Wood leads major charging infrastructure analysis initiatives at NREL for DOE, and numerous other federal, state, and industry sponsors. He is the overall lead for NREL's flagship Electric Vehicle Infrastructure – Projection (EVI-Pro) tool, along with the broader EVI-X modeling suite[42,43], and studies of both home and public charging access[11]. He will have minimal time planned on the project, but will provide a valuable consulting and advising role, plus will ensure any useful insights coming out of other charging infrastructure related projects are available to this project, and correspondingly that outcomes from this project are made accessible for the benefit of other projects.

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