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US-Mexico second-hand electric vehicle trade: Battery circularity and end-of-life policy implications

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ABSTRACT

Second-Hand (SH) vehicle imports from the US comprise nearly 30 percent of Mexico's light-duty vehicles. As US electric vehicle (EV) adoption progresses, SH EVs will increasingly enter Mexico. SH EVs could speed vehicle electrification, but also present environmental and economic risks because they are larger and reach retirement faster than new EVs. Understanding future flows of used and new EVs into Mexico's fleet, and their expected retirement, is needed to understand if SH EVs provide a net benefit. This research uses system dynamics modeling to project future EV adoption and SH vehicle trade between the US and Mexico. Results show EVs will comprise nearly 50% of Mexico's fleet and up to 99% of SH imports by 2050, and SH EV batteries disproportionately contribute to the stock of spent EV batteries. Policies to ensure SH vehicle trade provides net benefits for the region include import and export battery state-of-health restrictions.

1. Introduction

1.1. Implications of EVs entering the international second-hand vehicle trade

International second-hand (SH) vehicle exports are a multi-billion-dollar market for the US (Canis et al., 2017), and an integral process in removing older vehicles from the road and enabling a robust new vehicle market, particularly as vehicle inspection and maintenance requirements, emission standards, and incentive schemes make replacement of existing vehicles with a newer fleet more attractive (United Nations Environment Programme [UNEP], 2019). Exports also influence purchases in the US new-vehicle market as demand for SH vehicles abroad puts upward pressure on the price of SH vehicles in the US, making it less attractive to purchase used vehicles relative to new ones (Coffin, 2015).

Despite a strong economy with manufacturing capacity and consumers with high purchasing power, the US' vehicle ownership rate has remained at around 800 vehicles per 1000 people for the past twenty years as the market saturated (United Nations Environment Programme, 2020; Davis et al., 2022). Increasingly, new vehicle purchases do not add to total vehicle stock but rather replace older

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vehicles that are being deregistered from US roads. Concurrently demand for affordable SH vehicles in lower- and middle-income countries (LMICs) has increased due to steadily rising vehicle ownership rates (Sperling et al., 2004; Ecola et al., 2019).

The coupling of these circumstances, a domestic surplus of deregistered vehicles and a demand for more affordable vehicles abroad has enabled the vigorous international trade of used vehicles. Between 5 % and 13 % of the US' total deregistered vehicles per year are exported, representing nearly 30 % of its total vehicle exports (United Nations Environment Programme, 2020). With the rise in electric vehicle (EV) adoption in industrialized nations promulgated as a climate change solution for the on-road transportation sector (U.S. Department of State, 2021), EVs will inevitably enter international SH vehicle markets, posing challenges and considerations for both exporting and importing countries.

For the US, exporting SH EVs may lead to mineral security challenges, as it could reduce the availability of critical minerals and materials needed for domestic lithium-ion battery (LIB) production and recycling, hindering the potential for a circular economy and increasing the reliance on foreign sources (The White House, 2022).

While EVs effectively eliminate pollution at the tailpipe, they are not free of environmental impacts. Greenhouse gases (GHGs) and other environmental impacts of concern are shifted upstream to power plants for electricity used to charge them, and throughout the EV value chain, particularly in the production and end-of-life (EOL) of batteries (Ambrose et al., 2020). EOL impacts are a function of available options for disposal, which include recycling, stockpiling or landfilling. Currently, recycling facilities and systems for LIBs are not available in many parts of the world, including Mexico and across Latin America. Where recycling does exist, such as the US, the current capacity is far below what will be needed as EVs begin retiring in large numbers. The other alternatives, including stockpiling and disposal in landfills, pose additional environmental risks. Stockpiling has a risk of fires or explosions, which release harmful toxic gases. Disposal of LIBs in landfills can also lead to fires or explosions, and lead to toxic chemicals leaching into the soil and water, causing environmental contamination, harm to crops, and risks to human health (Kendall et al., 2022).

Current infrastructure, management practices, and regulations are based on knowledge of conventional internal combustion engine vehicles (ICEVs). As a result, location-dependent power generation mixes, as well as unregulated or inefficient EOL management systems for EVs may significantly increase environmental impacts associated with widespread EV adoption. Introducing a radically new technology such as EVs into the current system without responsive measures in SH market regions may lead to unintended economic and environmental consequences and could have significant environmental justice implications if importing markets are unprepared to manage EVs, especially at the EOL. If impacts are not analyzed through the perspective of interdependent trade regions, policies designed to reduce impacts domestically may have the opposite effect abroad. For example, policies that increase the cost of gasoline in the US have been shown to increase exports of used vehicles, leading to increased emissions in importing countries (Davis et al., 2011).

Already, around the world, there are documented examples of early adopter countries that have incentivized imports of SH EVs and hybrid electric vehicles (HEVs) by removing age restrictions, taxes, and customs duties and these countries have begun experiencing some of the challenges described above (Kendall et al., 2023). For instance, Mongolia imports SH HEVs from Japan, mainly Toyota Priuses, which uses nickel-metal hydride batteries designed to be functional for about 15 to 20 years. The exported vehicles have an estimated age of 10–15 years, meaning there may be few years of remaining battery life in imported vehicles. Due to a lack of infrastructure in Mongolia to recycle the HEV batteries, they are typically disposed of in landfills, posing potential environmental harm (Wang et al., 2019; 2020).

Egypt, which has traditionally barred SH vehicle imports, permitted the import of SH EVs in 2018 (United Nations Environment Programme, 2020). However, existing regulations were not amended to reflect EV powertrains resulting in high costs for registration - costs which are partly based on engine power ratings to discourage inefficient vehicles. EVs have high-powered electric motors which were subject to the same fees, and thus new EV owners faced disproportionately high registration fees (El-Dorghamy et al., 2020). Additionally, a significant number of SH EVs in Egypt are imported from the US, while available charging stations have European standards. This mismatch requires the use of plug adapters, introducing an additional barrier for adoption.

In 2015 Sri Lanka implemented a taxation scheme which resulted in an increase in the import of over 100,000 SH HEVs and around 6,000 SH EVs by the end of 2017, making it Japan's second-largest market for used hybrids and EVs during those years. However, incentives were subsequently removed just a few years after implementation due to concerns surrounding charging infrastructure and the capacity to manage EOL batteries (Ministry of Environment of Sri Lanka, 2021).

While SH EVs present a number of challenges to importing countries, they may also present a potential opportunity for industrial development around refurbishing, repurposing and recycling of LIBs. The resulting products generated by these industries could then be consumed domestically or, for secondary materials, exported to countries with battery manufacturing capacity to support a circular LIB value chain. Additionally, this approach effectively mitigates the adverse environmental effects associated with battery disposal (Knöll et al., 2021).

1.2. US-mexico SH trade relationship

These issues will become critical for countries like Mexico, where SH vehicles have been introduced both legally and illegally from the US for nearly a century. As early as the 1920s farmers in Mexican border states started introducing them to support agricultural work. Later, Mexicans working in the US brought them back to their families in Mexico (Anguamea Martínez, 2022). By 1992, there were between 600,000 and 700,000 illegally introduced SH vehicles in Mexico's fleet, and by 2001, the number had grown to between 1.5 and 2.5 million (Centro de Estudios Sociales y de Opinion Publica [CESOP], 2004). Concerned about public safety, environmental pollution, and revenue collection, the federal government implemented at least 34 measures since 1978 to provide formal status and register the illegally introduced SH vehicles through programs, decrees, and laws (CESOP, 2019), with the most recent registration program launched in January of 2022.

Regular SH vehicle trade with Mexico began in 2005, enabled by provisions in the North American Free Trade Agreement (NAFTA). Since then, over 9 million SH light-duty passenger vehicles (LDVs) have been imported from the US,[1] representing almost 30 % of all LDV registrations in Mexico during this period. Enactment of NAFTA and its 2020 revision, the United States-Mexico-Canada Agreement (USMCA), institutionalized the long-standing trend of integration of the countries' automotive industries, making cars and car parts the highest traded commodities in volume and value among the three (Angeles Villarreal et al., 2021). Regarding SH vehicle trade, for Mexico, adherence to NAFTA meant opening its market to its North American counterparts by gradually removing barriers to importing SH vehicles from the US and Canada, though Canadian trade represents less than 1 % of SH vehicles entering Mexico's market (Agencia Nacional de Aduanas de Mexico [ANAM], 2023).

Fig. 1 shows Mexico's yearly volume of SH vehicle imports from the US based on import data from Mexico's National Customs Agency (ANAM, 2023).

Initially, imports surged following the removal of age and environmental restrictions. However, Mexican auto manufacturers, policymakers, and NGOs expressed concerns about the harmful environmental implications of importing large volumes of advanced-age vehicles without proper environmental controls. They also pointed out the unfair market competition and its impact on the domestic car industry. In response, policy mechanisms were proposed and enacted to regulate the import of SH vehicles, and by 2015, restrictions began taking effect, normalizing the flow to current levels of just under 200,000 SH vehicles per year.

Despite the opposition, for large segments of the population, particularly low- and middle-income communities, SH vehicle imports represent affordable mobility options and serve as a means to access job opportunities and support their livelihoods. Supporters of this trade, including importers, dealers, and consumer protection associations, argue that it not only stimulates consumer spending but also creates job opportunities and bolsters vital sectors of the Mexican economy that are primarily occupied by low-income households. These sectors encompass services related to legally imported vehicles, such as mechanics, body repair workers, dealers, lot owners, upholsterers, auto parts shops, junkyard operators, and intermediaries facilitating transactions (Flamand et al., 2015).

Considering (1) the anticipated challenges and opportunities arising from the introduction of EVs into the global SH vehicle market, (2) the well-established US-Mexico SH vehicle trade and how integral it has become for the economy and livelihood of low and middle-income communities in Mexico, (3) the increasing regional trade integration under the USMCA and nearshoring policies to enhance supply chain resilience (The White House, 2021), and (4) the rapid growth in US EV demand projected over the next decade (a 700 % increase from 2022 sales of 990,000 units (International Energy Agency [IEA], 2023), there is a critical need for research to understand the future of SH EV trade in the region, as well as the environmental implications of SH EV trade policies to support a successful transition that minimizes environmental burdens and maximizes benefits for the region.

To fill this gap in knowledge, this research seeks to answer the following questions::

1. What will the volume of EVs entering Mexico via the SH and primary markets look like in the future, and what policies and infrastructure will be required to manage them at their EOL?
2. What will the material intensity of SH EV trade be, how might Mexico benefit from it, how might it affect the potential to retain critical battery materials in the US, and what are some potential regional cooperation scenarios to maximize bilateral benefits?

Results from this work could help the federal and state governments of the US and Mexico to design policies and regulations to manage trade of SH EVs to best benefit the region, and to develop policies and infrastructure to support recycling of EVs, and particularly their batteries, at their end of life.

1.3. Literature review

Research on the topic of US-Mexico SH vehicle trade ranges from the economic implications for one country or the other, to the effects it has on vehicle stocks in both nations, as well as the environmental consequences for Mexico.

In 2008, Cruz-Rivera and colleagues published some of the most comprehensive analyses regarding EOL vehicles in Mexico (Cruz-Rivera, 2008; Cruz-Rivera et al., 2008, 2009). Their work covered various aspects of EOL vehicles, including estimating the current and future number of EOL vehicles in Mexico by focusing on the impact SH vehicle imports have on the increase of EOL vehicles in the country, proposing a comprehensive system for managing EOL, and exploring the feasibility of a closed-loop supply chain for collecting and disposing of these vehicles.

In 2011, a report commissioned by Mexico's Ministry of the Economy, and authored by the consulting firm AT Kearny, laid out how the deluge of SH vehicle imports had an important decelerating effect on new vehicle sales in Mexico during the early years of NAFTA because of the removal of SH vehicle import restrictions. The report also describes the significant effect salvaged vehicle arbitrage has on driving the SH vehicle market (Kearny, 2011). Salvaged vehicle arbitrage refers to the practice of procuring salvage or damaged vehicles in the US and selling them in Mexico for a profit. This dynamic is feasible because the cost of repairing vehicles in the US is

[1] Data from Mexico's National Customs Agency (ANAM) was used for calculations in this article instead of data provided by US ITA as it was found that export data from US ITA critically underestimates SH vehicle flows compared to import volumes reported by ANAM. This discrepancy in reporting is due to the shared land border, which allows large numbers of SH vehicles to be transported by road into Mexico without formal US export documentation and later registered legally through customs for use in Mexico. Therefore, using ANAM data collected directly from Mexican customs officials ensures more reliable information on the SH vehicle trade between Mexico and the United States.

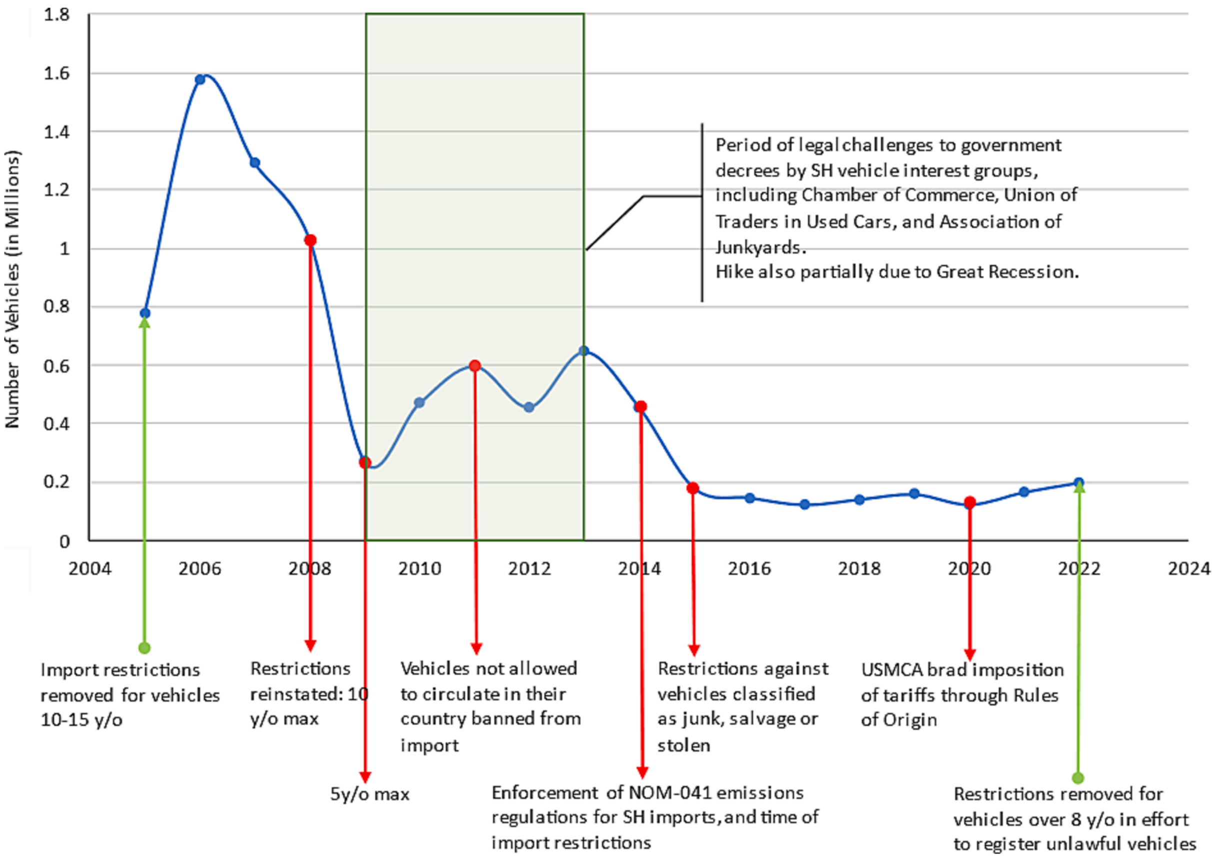

Fig. 1. Trends in SH Vehicle Imports to Mexico from 2005 to 2022. Illustrating the effect different policies and larger economic conditions had in shaping the trade. Adopted legislations were compiled by the author through various news outlets and official government notices published in Mexico's Diario Oficial de la Federación (DOF) (Secretaría de Gobernación, 2023), the official journal of the Mexican government where new laws, regulations, and other official communications are published. *The abbreviation "y/o" in the figure is used to represent "years old".

significantly higher than in Mexico, making it more attractive for US consumers to opt for new or used cars with a clean title, particularly with leasing or financing options available. Acquiring a vehicle with a salvaged title in the US would require significant time and financial investments for repairs and inspection procedures to obtain a new title. These expenses may often exceed the vehicle's price, and even after successful retitling, the vehicle's history as a salvage-titled vehicle may affect its resale value and insurability.

Conversely, in Mexico, repair costs are comparatively affordable, and enforcement of environmental and road safety regulations is less stringent. Thus, the relative value of damaged vehicles is higher for Mexican consumers than for their US counterparts. Mexican buyers, therefore, are willing to pay a higher price for these vehicles, as they can be easily repaired, registered, and legally driven in Mexico. This practice contributes to the flow of SH vehicles from the US to Mexico and shapes the market between the two countries.

In later work, Coffin et al., (2016) examined barriers to the US' SH vehicle trade using a gravity model to estimate how policies from 140 countries limited SH vehicle exports from five of the top exporting countries. Canis et al., (2017) found that motor vehicles and vehicle parts, both new and used, accounted for more than 20 % of the total value of US merchandise trade with Canada and Mexico in 2016, making them the largest category of manufactured products traded among the United States, Mexico, and Canada.

Other research has focused on the environmental implications of SH vehicle trade. In work focusing on air quality pollutants, Davis et al., (2011) found that SH vehicles are dirtier than the stock of vehicles in the US but on average cleaner than the stock in Mexico, so when a vehicle is traded from the US to Mexico average vehicle emissions per km tend to decrease in both countries. Overall, however, the evidence suggests that trade has increased total lifetime emissions per vehicle, primarily because of low vehicle retirement rates in Mexico (Davis et al., 2010).

Research published by Macias et al., (2013) confirms that for exporting countries, there might be a moderate reduction of GHG emissions due to SH vehicle exports. However, many of these vehicles failed smog and road safety checks in their original countries and could no longer be used according to environmental criteria, leading to the decision to export them to countries with weaker regulations. In importing countries like Mexico, vehicles are used for many more years, some of them up to 30 years. This results in an increase in GHG and criteria pollutant emissions, fuel waste, and road safety problems. In addition to the extended total lifetime emissions issue, research by Flamand et al., (2015) finds that Mexican cities along the border with access to affordable SH vehicles from the US, more than 80 % of the vehicles in use are SH imports. The access to vehicles at prices on average 40 % lower than purchasing vehicles produced in Mexico has resulted in notably elevated motorization rates in border cities, ranging from 600 to 800 vehicles per thousand residents. This rate is two to three times higher than the major urban hubs of Mexico City, Guadalajara, and Monterrey. Moreover, nearly half of these SH imports are large, segment 2 and 3 vehicles (SUVs, vans, and pick-up trucks) with higher fuel consumption compared to smaller, compact, and subcompact domestically manufactured vehicles, resulting in elevated emissions of greenhouse gases.

There is also a body of work focused on global SH vehicle trade and its environmental and transportation justice issues that has emerged from the UN Environment Programme's Sustainable Mobility Unit. Recent reports include the 2020 report entitled Used Vehicles and the Environment, and an update that followed in 2021 (United Nations Environment Programme, 2020; UNEP, 2021). These reports present the first global study of the trade of used LDVs, providing estimates of globally traded SH vehicle flows and exploring some of the drivers, impacts, and policies regulating them. The findings of these reports highlight a significant rise in the export of used LDVs, predominantly from high-income to lower-and middle-income nations. Many of these vehicles are characterized as aged, inefficient, polluting, and lacking in safety standards. The absence of standardized minimum quality requirements for used LDVs on a global or regional level emerges as a pressing concern, with far-reaching implications for climate change, air pollution, road safety, and public health. Drawing from effective, existing best practices and regulations in reviewed countries, the reports advocate for establishing harmonized minimum quality standards for used LDVs in response to these challenges.

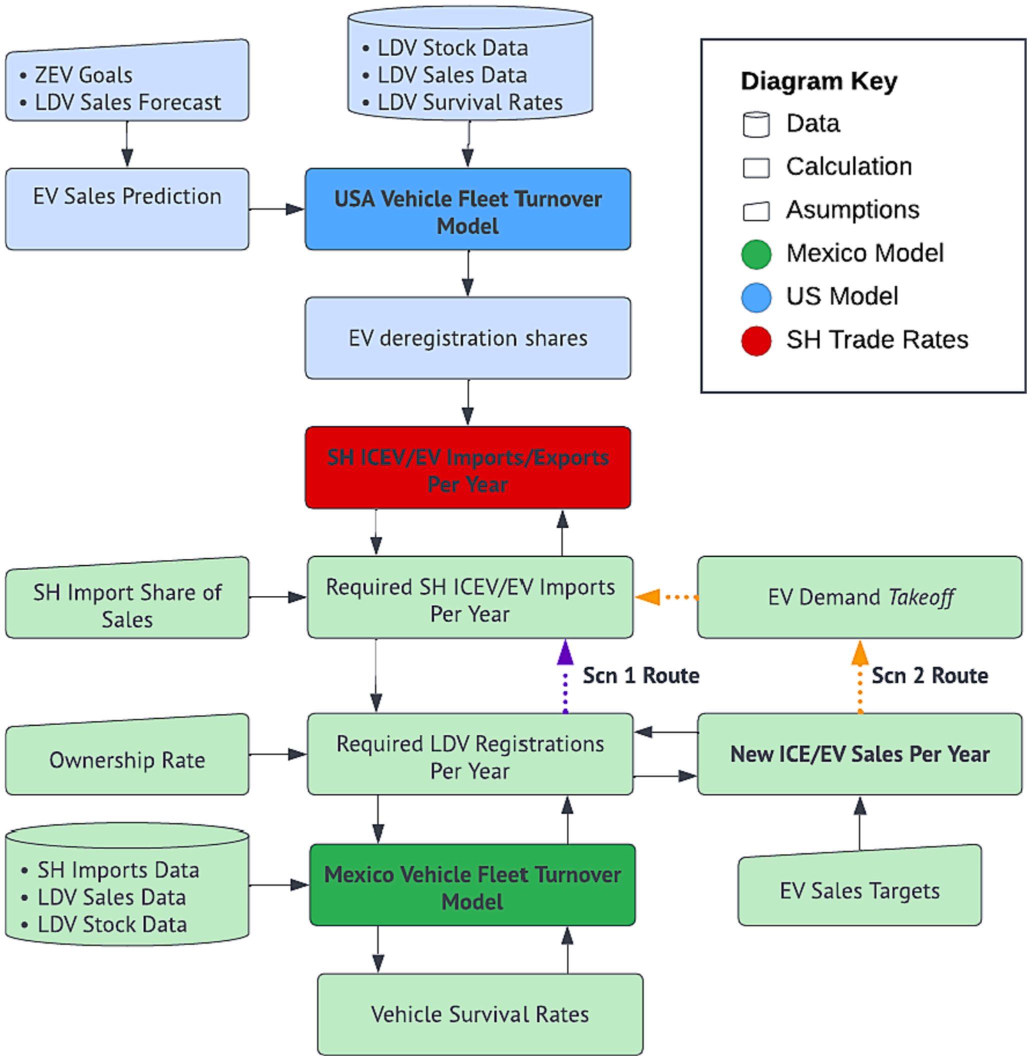

Fig. 2. Flow diagram illustrating the full modeling process. Input data, assumptions, calculations, and values regarding the fleet turnover model in the US are depicted in blue, while corresponding information for Mexico is in green. The process where the output from the US' fleet model feeds into Mexico's, resulting in the yearly volume of traded SH vehicles, is depicted in red. Scenario 1 (Scn1)and Scenario 2 (Scn2) routes indicate the different pathways to calculating the volumes of SH ICEVs and EVs required to meet demand in Mexico. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A parallel landmark study carried out by the Human Environment and Transport Inspectorate (ILT) in the Netherlands and the United Nations Sustainable Mobility Unit was performed regarding the quality of used vehicles exported to countries in North and West Africa. The study found that by the end of the study period in 2020, 80 % of the used vehicles exported to North and West Africa were below the Euro 4/IV emission standard, and did not meet the criteria for a roadworthiness certificate in the country of origin. Additionally, the study found that most of these used vehicles would no longer be acceptable in importing West African countries as they moved to adopt the stricter Euro 4/IV emission standard as a region by 2021, with a 10-year compliance period. The study recommends a coordinated approach among European countries to address the environmental burdens passed onto receiving nations via the SH vehicle trade (ILT, 2020).

Finally, a related publication by the German Corporation for International Cooperation (GIZ) from their Advancing Transport Climate Strategies (TraCS) project discusses Kenya's EV landscape, addressing the issue of EOL EV batteries, a particularly salient issue given that SH imports comprise 80 % of Kenya's vehicle fleet. The article proposes using second-life applications to prolong EV batteries' life and to integrate them into a larger circular economy until profitable recycling solutions are available. It also suggests learning from successful battery management projects in India and Nigeria and adopting legislation from industrialized nations aimed at developing a circular battery economy (Knöll et al., 2021).

As demonstrated by the existing literature examining SH vehicle flows, few studies have focused on EVs, and none have focused on US SH EV trade, let alone with Mexico.

2. Methods

This research uses a modeling approach to predict the future flows of SH EVs into Mexico to understand their timing and magnitude. The modeling process consists of three main parts, as shown in Fig. 2. First, a stock turnover model is developed to forecast the volume of deregistered EVs and ICEVs in the US through 2050. A stock turnover model uses historical data on vehicle stock size, age-dependent scrappage rates, and new vehicle sales to forecast future vehicle stock levels and technology mix (Hao et al., 2011). Second, we create a similar stock turnover model for Mexico to forecast total light duty vehicle (LDV) sales and SH imports, as well as their composition by vehicle technology. Finally, two SH import scenarios are used to estimate the number of EVs entering Mexico through the SH market.

2.1. US stock turnover model

2.1.1. Vehicle sales projection

We forecast new EV sales in the US through 2050 using the U.S. Energy Information Administration's (EIA) 2022 US total vehicle sales forecast (EIA, 2023). A linear projection of EV sales to 2050 is then made by applying the 2021 White House goal to make zero emission vehicles (ZEVs henceforth referred to as EVs) 50 % of total vehicle sales by 2030 (The White House, 2023), and extending the trend until achieving 100 % of sales. While the White House target is ambitious and EV adoption rates will be contingent upon a spectrum of variables such as EV prices, range, and the extent of accessibility to a comprehensive and widespread charging network, we peg our forecasts to government policy targets because they have been the drivers of EV supply and adoption across the world (IEA, 2021). Competing approaches to estimating future vehicle sales do not embed current and future state and federal policies and incentives that drive industry investments and EV purchases in the marketplace. We use the R stats package (version 4.4.0) (R Core Team, 2022) to fit three probability distributions commonly used for growth models to our data: the Gompertz, Weibull, and Logistic models.

2.1.2. LDV retirements

To calculate the volume and rate of light duty EV retirements per year in the US from 2010 to 2050, we used vehicle stock turnover modeling based on the methods described in (Wang et al., 2019). The model is based on the equation:

$$Y^t = Vst^{t-1} + Vs^t - Vst^t \tag{1}$$

Where $\mathbf{Y^t}$ represents the number of deregistered vehicles in a given year, $\mathbf{Vst^{t-1}}$ is the previous year's stock, $\mathbf{Vs^t}$ is the current year's sales, and $\mathbf{Vst^t}$ is the current year's stock.

The survival of vehicles from one year to the next is determined by a "survival rate" factor that follows an inverse sigmoidal curve related to the deterioration process of vehicles. These survival rate curves are commonly calculated by fitting the Weibull survival model to historical vehicle stock and deregistration data. The resulting curve is unique to each country and is influenced by the local driving and maintenance habits and economic factors of the population.

The stock is thus broken down by vehicle age, assigning each cohort the appropriate survival rate factor through:

$$Vst^t = \sum_{j=1}^{m} \left[Vs_{j-1}^{t-1} * Sr_{j-1} \right] \tag{2}$$

Where $\boldsymbol{j}$ is the vehicle age cohort, $\boldsymbol{m}$ represents the maximum possible age achieved by vehicles, Vs_{j-1}^{t-1}represents the number of vehicles in the preceding cohort for the previous year, and $\boldsymbol{Sr}$ is the survival rate factor for each age cohort.

As EV LIBs undergo cycling and aging, they experience degradation that can eventually render them unsuitable for their initial purpose of powering a vehicle. While EV battery replacements do occur, they can be prohibitively expensive after the warranty period expires (typically 8 years). Therefore, in cases where the rest of the vehicle is also aging, the entire vehicle might be retired along with the battery. Based on manufacturers' descriptions and current literature, once EV LIBs are degraded to 70–80 % of their nominal capacity, their useful lifespan in an EV ends. Estimates place this useful lifespan between 100,000 and 200,000 miles, or between a low of 8 to a high of 20 years (Gasper et al., 2022), contingent on a number of influencing factors, including temperature, cycling patterns, and operating windows (Ai et al., 2019; Casals et al., 2019; Hussein et al., 2021). A challenge for predicting EV battery lifetime is that battery technology and EV design have changed rapidly, and relying on historical information for battery life likely underestimates the lifetime of batteries sold in vehicles today.

At the upper limits of current expected battery lifetime, EV LIBs will meet or exceed the expected lifetime of today's ICEVs, which have a median life of about 15 years. In cases where battery replacements occur, we would expect lifetimes that meet or exceed ICEV lifetimes. While there is a risk that lower average LIB lifetimes might cut short EV lifetimes compared to ICEVs, we have assumed equivalent deregistration rates for EVs and ICEVs and use the estimated survival rates for cars in the US published in the Oak Ridge National Lab Transportation Energy Data Book: Edition 40–2022 (Davis et al., 2022).

We selected 2010 as the first year for our model as it is the first year with registered EV sales in the US. Then, we used the historical and forecasted ICEV and EV sales (EIA, 2023)in combination with the provided survival rates as input for our stock turnover model to calculate the total ICEV and EV stock and deregistrations separately from 2010 to 2050.

The age distribution for the initial year was calculated using the percentage breakdown of US LDVs in operation by age for 2013 (Davis et al., 2022) and applied the ratios to the total reported vehicle stock for 2010 (EIA, 2023).

Historical customs data indicates that the average exported vehicle to Mexico is between 5 and 9 years old (ANAM, 2023). Tracking both technologies in our model separately enabled us to calculate the share of 5–9-year-old vehicles being deregistered in the US that were EVs or ICEs, respectively, every year for the period of interest. We then assumed SH exports to Mexico to reflect the same technological composition.

2.2. *Mexico stock turnover model*

A large stock of deregistered EVs in the US is insufficient to cause SH EV trade there must also be sufficient demand for SH EVs in Mexico (United Nations Environment Programme, 2020). To estimate a projection of the growth of both the new and SH EV markets, we built a stock turnover model for Mexico that accounts for the total EV stock in the country, the technological composition of new sales and SH imports, as well as the technological composition of yearly retirements for both categories. First, we used data for SH vehicle imports provided by Mexico's National Customs Agency (ANAM, 2023) in addition to historical vehicle fleet and yearly ICEV and EV sales data from the National Institute for Statistics and Geography (INEGI) (INEGI, 2023) to populate the model from 1980 to 2022. Only SH vehicles from the US are included in the model as they comprise 97 % of all SH imports. Then we calculate the survival rates per vehicle age using Excel Solver to optimize the mean absolute percentage error (MAPE) and mean absolute error (MAE) model performance metrics between our model output and Mexico's historical in-use stock and deregistration data.

We then assume a 2050 total stock target based on estimates by the International Council on Clean Transportation (ICCT) (ICCT, 2022)and the International Energy Agency's Mobility Model (Momo) (IEA, 2022) for Mexico's vehicle ownership rate of close to 300 vehicles per 1000 people. Using the calculated target stock and the optimized model survival rates, we were able to infer the yearly LDV registrations required to achieve the stock target.

To estimate the volumes of future SH imports and new sales in the country, we calculated the mean annual ratio of SH imports to new registrations over the past five years (11.5 %) and, given the consistent trend of SH imports since 2015, as shown in Fig. 1, we assumed that this rate would remain constant until 2050.

Our model tracks and classifies yearly vehicle registrations (new sales and SH imports) according to their propulsion technology. To predict new EV sales, we use Mexico's National Electric Mobility Strategy (NEMS) EV sales targets (SEMARNAT, 2023), to be adopted in 2023 (Portal Movilidad, 2023). This strategy aims for 5 % of total LDV sales to be EVs by 2030, 50 % by 2040, and 100 % by 2050. We apply these targets to the new LDV registrations per year calculated in the previous step to create a linear projection of new EV sales in Mexico up to 2050. Then, we simulated an ideal growth scenario by fitting the same common probability distribution functions as for the US model (Logistic, Weibull, and Gompertz) to the linear projection, ultimately selecting the Weibull as it produced the best R2, RSE, MAE, and MAPE performance metrics fit.

To estimate the composition of vehicle technologies for SH imports to Mexico, we created two different scenarios as detailed in the following section.

2.2.1. *SH import scenarios*

2.2.1.1. Scenario 1. Scenario 1 is based on the output of the US stock turnover model, which calculated the percentage of 5–9-year-old vehicles that were EVs or ICEVs from 2010 to 2050. By applying these shares to the projection of SH imports, we estimated what the composition of vehicle technologies for SH imports to Mexico would be as EVs begin to enter the deregistered stock in the US. In this scenario Mexico's imports of SH EVs are driven by their availability in the stock of US deregistered vehicles, implicitly assuming that there is sufficient demand.

2.2.1.2. Scenario 2. Scenario 2 treats Mexico's demand for SH EVs through the lens of Diffusion of Innovations, in which the adoption of new technologies, such as EVs, follows three distinct phases. In an initial formative phase, high costs and uncertainty result in slow and erratic growth. This phase ends with take-off when the sociotechnical regimes formed around new technologies become capable of steady expansion. This kicks off the growth phase, in which growth accelerates due to positive feedback in economic profitability, technology learning, and policy support. After achieving its maximum level, growth begins to slow down due to factors including increasing marginal costs, geophysical constraints, or countervailing political and social resistance, which lead to a saturation phase when the market penetration of the technology no longer increases (Cherp et al., 2021).

Therefore, scenario 2 is based on the assumption that SH EV imports would only take off once there was enough cultural acceptance, as well as legislative, financial, and technical infrastructure in place to support the development of a SH EV market in Mexico. To estimate this moment, we used the take-off period for new EV sales in Mexico as a proxy for the starting point of SH EV imports under the assumption that SH EV adoption would be encouraged by the same conditions as new EV adoption.

We use two complementary methods from differing fields to calculate when the EV market in Mexico will enter its growth phase of rapid expansion. First, an empirical method widely used in market research that estimates a range during which the take-off period of a new technology may occur based on consumer behavior observations. Then, to validate our results and establish a specific year for further calculations, we apply a mathematical approach widely used in population dynamics that non-arbitrarily defines the point of take-off by calculating the maximum acceleration of the growth rate of a growth curve. The two methods are described in more detail bellow:

2.2.1.3. Take-off method 1: Diffusion of Innovations (DOI) estimation. The first method is based on the theory of DOI (Rogers, 1962), which proposes that for a technology to achieve its point of take-off and enter its growth phase, 10–20 % of total market capacity must already be realized. This estimation is based on well-documented cases of market behavior in which early adopters, roughly 16 % of potential consumers according to DOI adopter categorization, fully appropriate a new technology and reach a critical mass that is strong enough to influence their peers and catalyze sustained rapid expansion.

To estimate the EV market capacity in Mexico by 2050, we utilize our model's predictions for new EV sales and calculate the period during which EVs are expected to represent 10–20 % of the total market capacity.

2.2.1.4. Take-off method 2: Parametric definition of the lag time. This method is widely used to calculate the lag time in population growth dynamics (Buchanan et al., 1990; Zwietering et al., 1990). Lag time refers to the period that occurs between the initiation of a growth process, the time at which a population is its original size, and the onset of sustained exponential growth defined as the point at which the growth rate achieves its maximum acceleration. It can be determined by fitting a growth curve to a sigmoidal parametric model (Gompertz, Logistic, Weibull) to estimate it's parameters. Then, the first and second derivatives of the growth curve can be calculated and used to find its point of inflection. By extrapolating the tangent of the inflection point to the intersection with the line $P(t) = P_0$, where P_0 is the population's original size, we arrive at the time at which *lag time* ends and *take-off begins*. See Fig. 3 for clarity.

While this method is widely used in microbiological growth studies, it is based on the geometry of sigmoidal growth curves and not on particularities of microbiological dynamics. Thus, it can be applied in any context where growth can be modeled by a sigmoidal function, such as population growth, market growth, and technological diffusion, among others (Grübler, 1990).

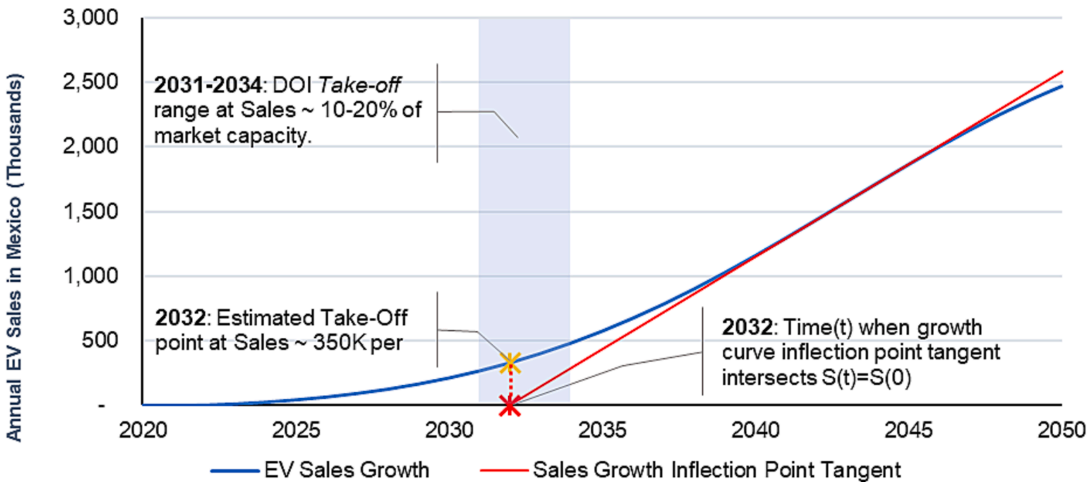

Fig. 3. Projected annual EV sales in Mexico for two sales take-off methods. This figure was created using the EV sales growth projection from our modeling, it is meant to illustrate both sales Take-off estimation methods used and the degree to which they align and reinforce each other. The dotted line between the red and yellow stars is a visual aid illustrating that the time at which the inflection point tangent intersects $S(t) = S(0)$, is also the time at which the Take-off point is estimated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Therefore, we estimate the period at which the EV market in Mexico will begin expanding rapidly by fitting the three previously used growth models to the forecast of new EV sales in Mexico and extrapolating the tangent at its point of inflection to the line $S(t) = S_0$, where S_0 is sales equal to zero.

Finally, we input both scenarios into our model, allowing us to consider the impact of the availability of deregistered vehicles in the US as a force pushing exports into Mexico, and local demand as a force pulling them in. Thus, arriving at a more comprehensive understanding of the evolution of the SH vehicle market in Mexico.

2.3. Battery capacity and mass entering Mexico

To estimate an average battery capacity for EV models sold in the US and in Mexico, we calculated a sales-weighted average EV (including PHEVs) battery capacity for both countries based on data from EV Volumes on vehicle sales (EV-volumes.com, 2023b) and installed EV battery sizes per country (EV-volumes.com, 2023a). Then, we calculate the total LIB mass becoming available yearly in Mexico from deregistered EVs (purchased new or imported SH) using BatPaC v5.0 (Argonne National Laboratory [ANL], 2022) to obtain battery pack specifications, including energy density and battery pack weight, the average historical chemistry of battery cells (EV-volumes.com, 2023a), as well as a projection of future chemistries.

Lithium Nickel Cobalt Aluminum Oxide (NCA) and Lithium Nickel Manganese Cobalt Oxide (NMC) LIB chemistries currently dominate both the US and Mexican EV markets (EV-volumes.com, 2023a). However, both these chemistries contain cobalt. There is a push to reduce cobalt content in LIBs due to its high cost and environmental, social and governance issues in its mining, which is dominated by mines in the Democratic Republic of the Congo (Sovacool et al., 2020). Lithium Iron Phosphate (LFP) batteries are the dominant cobalt free LIB alternatives and have the benefit of being lower cost as well. Large EV auto manufacturers in China have led in LFP adoption, investing heavily in LFP technologies for several years. Recently US and European OEMs like GM, Ford, BMW, and Tesla have announced investments in LFP technology and shifts towards LFP batteries for specific models (GITLIN, J.M., 2021; Kane, 2021; Bellan, 2023; Rosevear, 2023). These trends indicate a likely evolution toward adopting LFP LIBs in vehicles sold in the US and Mexico. Thus, chemistries are modeled to evolve following a linear progression from today's NCA and NMC mix to a mix comprised of equal parts NCA, NMC and LFP in 2050. Our assumption for identical battery chemistry evolution in the US and Mexico is based on ongoing regional integration (The White House, 2022) and global (not just US) industry trends and advancements favoring LFP.

Finally, using estimated recoverable amounts of materials per battery pack type at their EOL (ANL, 2022), we calculate the mass of recoverable materials, including:

- Lithium: From battery electrode, electrolyte, and additives.
- Nickel, cobalt, manganese: From electrode.
- Aluminum: From current collectors, terminals, thermal conductors, interconnects, bus bars, and pack jackets (excluding aluminum foil in multilayer cell container and aluminum in electrode materials).
- Copper: From current collectors, terminals, thermal conductors, interconnects, bus bars, and pack jackets.
- Steel: From structural and cooling components in the pack.

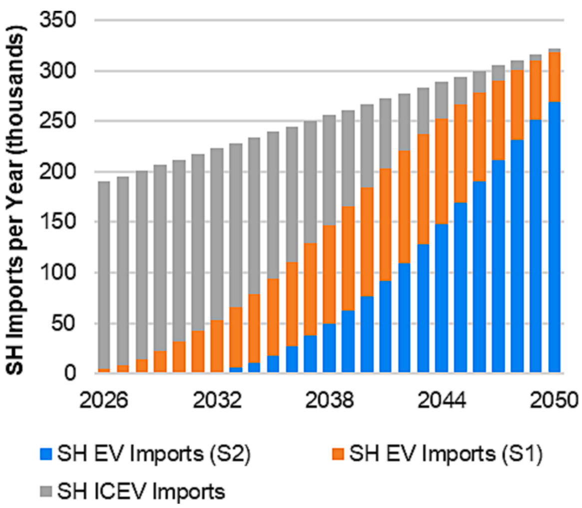

Fig. 4. Projections of Total Second-Hand Vehicle Imports to Mexico: In conditions where Scenario 2 occurs, the area labeled S1 will be comprised of SH ICEV imports, under conditions where Scenario 1 occurs, the area labeled Scenario 2 is included in the total SH EV imports.

3. Results

3.1. SH vehicle imports projections: Scenario 1 vs Scenario 2

Fig. 4 shows the projections of total SH vehicle imports to Mexico for the study period, as well as the breakdown of imports between SH ICEVs and EVs, for the two scenarios described previously. The figure indicates a growing trend in SH vehicle imports to Mexico over time, with most imports being SH ICEVs. The share of imported SH EVs in **Scenario 1** kicks off earlier assuming that SH EVs are imported to Mexico as they become available in the pool of the US' 5–9-year-old deregistered vehicles, increasing over time to reach 99 % of yearly SH imports by 2050 and a cumulative 3.8 million units imported. The number of imported SH EVs in **Scenario 2** is zero until 2033, assuming that SH EVs are only imported after the new EV market in Mexico has reached its take-off point, after which it starts to increase significantly, reaching 84 % of total SH imports by 2050 and a cumulative 2.08 million units imported.

Based on Mexico's NEMS strategy, we expect EV sales in Mexico to continue to increase rapidly, with an estimated growth rate of around 30 % per year over the next decade, the uptake of SH EVs is expected to grow more slowly, as the pool of available used EVs is still relatively small. However, by the mid-2030 s, as the number of used EVs on the market begins to increase significantly on the US side, the market for SH EVs will start to develop and gain momentum.

Once the market for SH EVs has established, it is expected to experience sustained growth, driven by a combination of factors including declining costs, increasing consumer confidence in the technology, improved reliability and performance, as well as government incentives and regulations aimed at promoting EV adoption.

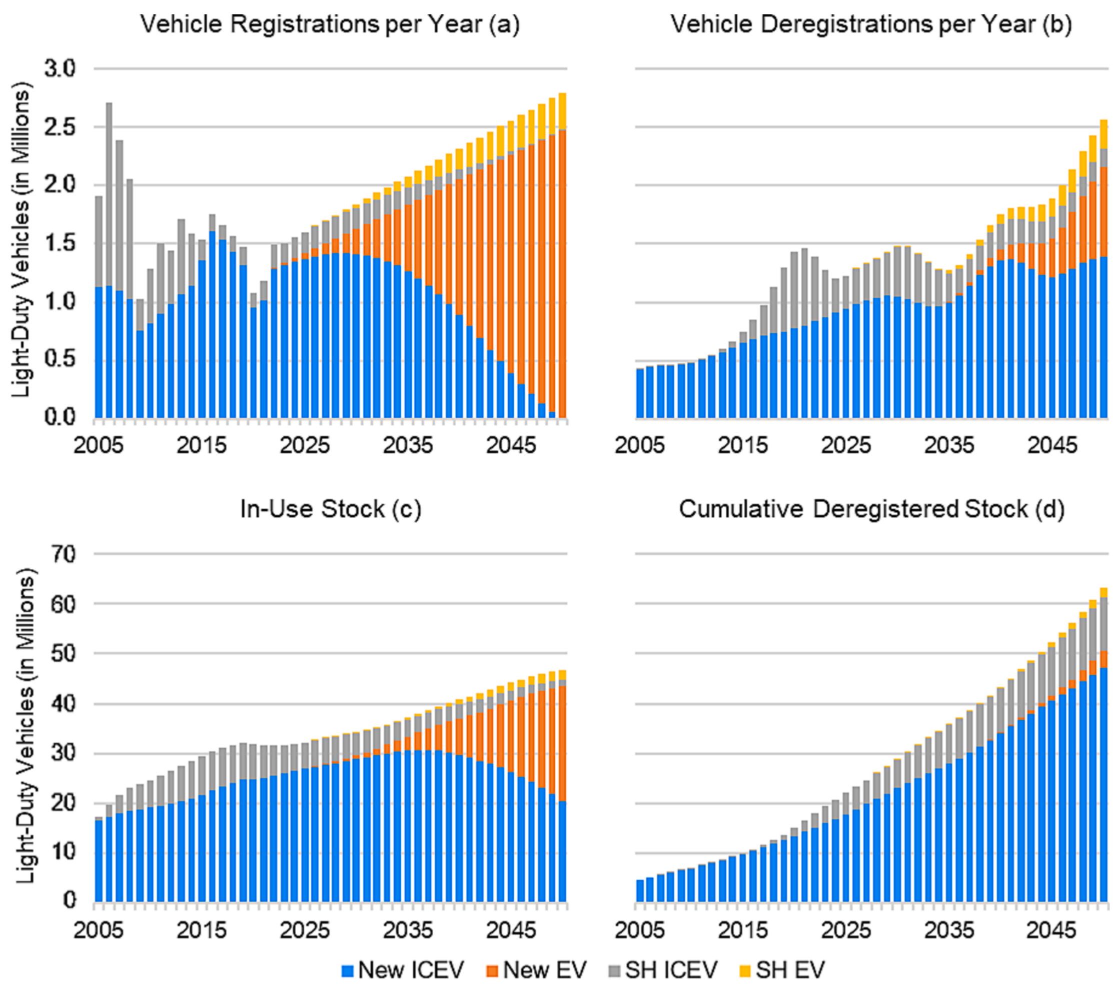

Fig. 5. Shift in the composition of yearly LDV registrations (a) and deregistrations (b) in Mexico. Evolution of the composition of the Mexican In-Use (c) and Deregistered (d) Vehicle Stocks.

3.2. Scenario 1 analysis

The following sections focus exclusively on the results obtained from Scenario 1, detailed results from Scenario 2 are available in the Supplementary Material associated with this article.

3.2.1. Evolution of vehicle registrations and deregistrations

Fig. 5 presents a side-by-side comparison of the total yearly vehicle registrations in Mexico broken down by propulsion technology and origin (Fig. 5**a**), and the total yearly deregistrations (Fig. 5**b**) in the country similarly broken down by origin and technology. It illustrates the gradual shift to EVs encouraged by its NEMS targets, and the time at which new and SH EVs begin reaching their EOL. Also, it allows to assess the differential rates at which EVs and ICEVs reach their EOL in the country.

Fig. 5**c** shows that until 2005, the total in-use vehicle stock in Mexico was approximately 16.23 million vehicles, with 100 % of them being domestically sold ICEVs. From 2005 to 2015, the total in-use vehicle stock in Mexico increased significantly, driven in large part by SH imports from the US. However, due to higher rates of retirement and the normalization of the flow of SH imports following the series of import regulations adopted by Mexico (Fig. 1), the share of SH vehicles in the in-use stock will decrease over the observed period, from a high of 26 % in 2014 to 7 % by 2050.

Although they continue representing a very small percentage of vehicles on the road, EVs were first sold in the country in 2016. Fig. 5**c** shows that as EVs become more prominent in the market, they progressively occupy a larger share of the new and SH in-use stocks, reaching 53 % and 62 %, respectively, by 2050.

The cumulative retired LDV stock is shown in Fig. 5**d**. Following the removal of SH import restrictions, the stock of SH ICEV deregistrations gradually increased in 2006, reaching 1 % by 2014 and peaking at 22 % around 2035. Subsequently, the share of SH ICEVs begins to decline due to the combined effects of import restrictions implemented between 2008 and 2014 and the introduction of SH EVs. By 2050, the share of SH ICEVs in the retired vehicle stock will reach 17 % while SH EVs reach 3 %.

Notably, modeling reveals that while new and SH vehicles are consistently integrated into Mexico's in-use fleet, each contributing a median of 5.52 % and 6.49 % annually over the period to the new and in-use stock, respectively, SH vehicle imports hold a smaller share of the in-use stock relative to their input volumes because they have a significantly higher rate of deregistration than new vehicles. SH vehicles reach deregistration at a median rate of 7.3 % per year, while new vehicles are deregistered at a lower median rate of 3.3 %. Thus, despite their similar entry rates, the accelerated deregistration of SH vehicles causes them to spend less time in the in-use stock and reach their EOL faster than new vehicles, contributing disproportionately to Mexico's deregistered vehicle stock. To

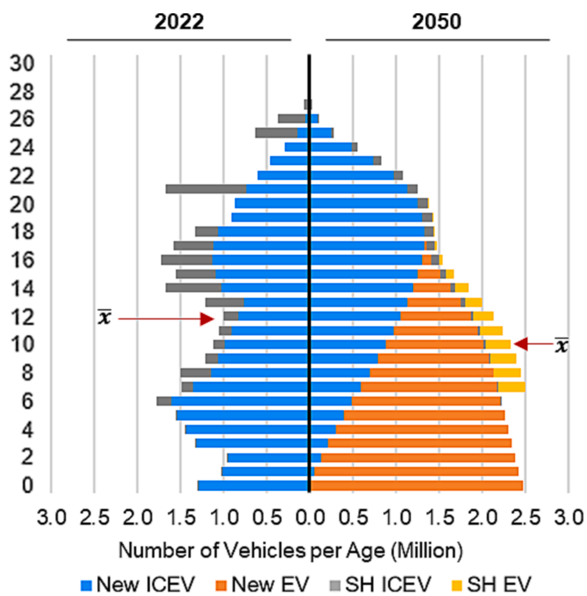

Fig. 6. Side by side comparison of the age composition of the vehicle fleet in Mexico in 2022 against our model prediction for 2050 Left: Age Distribution of the Mexican in-use vehicle stock by propulsion technology and origin, 2022. Right: Age Distribution of the Mexican in-use vehicle stock by propulsion technology and origin, 2050. The $\bar{x}$ on each side indicates the average age of the fleet.

illustrate, by 2050, SH retirements are cumulatively 20 % of total vehicles deregistered, though on average (between 2005 and 2050), they only comprise 11 % of vehicles on the road.

Overall, the data shows that the composition of the propulsion technologies of the vehicle stocks in Mexico is evolving, with a stabilization of SH import levels and a gradual shift towards EVs.

3.2.2. *Mexican LDV stock age and composition*

Fig. 6 is a side-by-side comparison of the age distribution of the Mexican in-use vehicle stock for the years 2022 and 2050. It is further broken down by propulsion technology, showing the origin and number of vehicles available per age group (0 to 30 years old) for the analyzed years.

In 2022, Mexico had a total in-use LDV stock of approximately 31.5 million, of which 81 % were new ICEVs and 19 % were SH ICEVs, accounting for almost 6 million. In contrast, the number of new EVs in use remains comparatively smaller, with only around 6,000 nationwide.

By 2050, Mexico's in-use LDV stock will grow to approximately 47.5 million although the share of new ICEVs will decrease to 43 %, while the share of new EVs will increase to 50 %. Similarly, SH ICEVs have decreased significantly to comprise only 2 % while the number of SH imported EVs has increased to 5 %.

Notably, the data also show that as new and SH EVs enter Mexico's vehicle stock, the average age of the fleet decreases. The weighted average age of the stock in 2022 was 12 years, but it decreases to 10 years in 2050, despite the stock being significantly larger. This decline is explained by current average battery lifetime estimates and the lack of battery maintenance and repairability and affordable battery replacements. This gradual decrease in fleet lifespan will increase stress on Mexico's EOL management system and may pose an important economic challenge as the country relies heavily on the extended operation of its vehicles and the underlying supportive maintenance and repair systems required.

3.2.3. *Cumulative new and SH EV flows*

Fig. 7 shows the total flow of EVs through Mexico from 2016, the first year of registered EV sales, to 2050. It shows the cumulative EV registrations over the period, including their origin and their status by 2050.

Calculations indicate that Mexico will import 3.8 million EVs from the US' pool of deregistered vehicles and there will be 26.5 million new EVs sold in the country, for a total 30.4 million EV registrations throughout the entire period.

Out of the total registrations during the period, 28 million will remain in use, while 3 million will reach their EOL. Among those reaching EOL, 1 million will be imported SH and 2 million will be newly purchased in Mexico. Fig. 7 further illustrates the faster retirement rate of SH EVs as compared to new ones. By the end of the analyzed period, 24 % of SH EVs entering Mexico will be deregistered, while only 7.6 % of new EVs will have reached EOL.

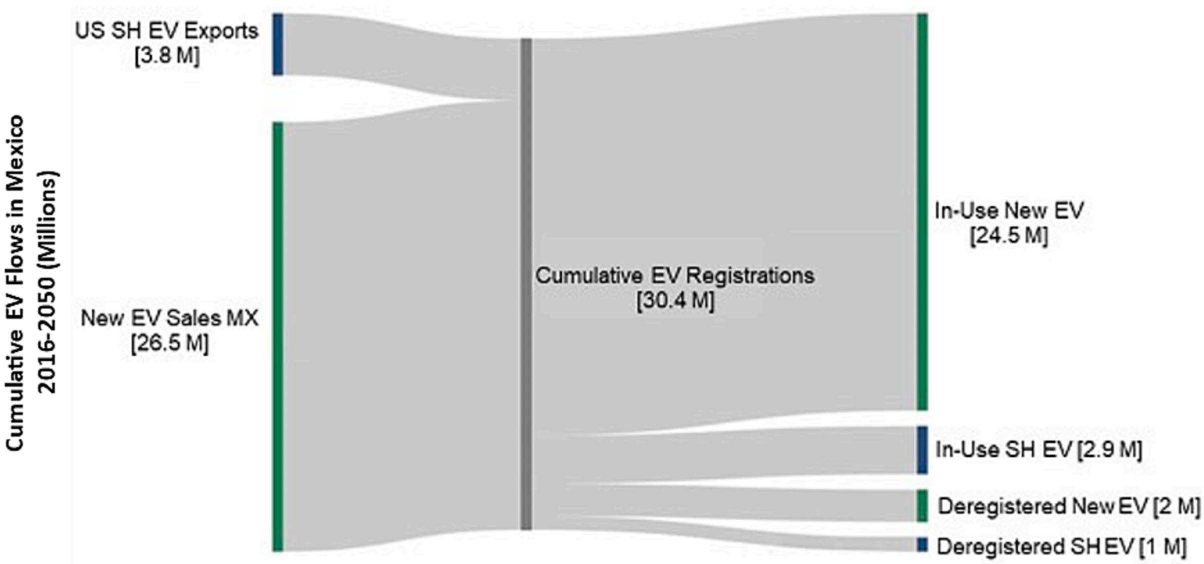

Fig. 7. Left: Cumulative EV flows entering Mexico from 2016 to 2050, depicted in millions, encompassing both imports of shared electric vehicles (EVs) from the US and new EV sales within Mexico. Right: Cumulative flows of EVs that remain in use, and deregistered EVs from 2016 to 2050.

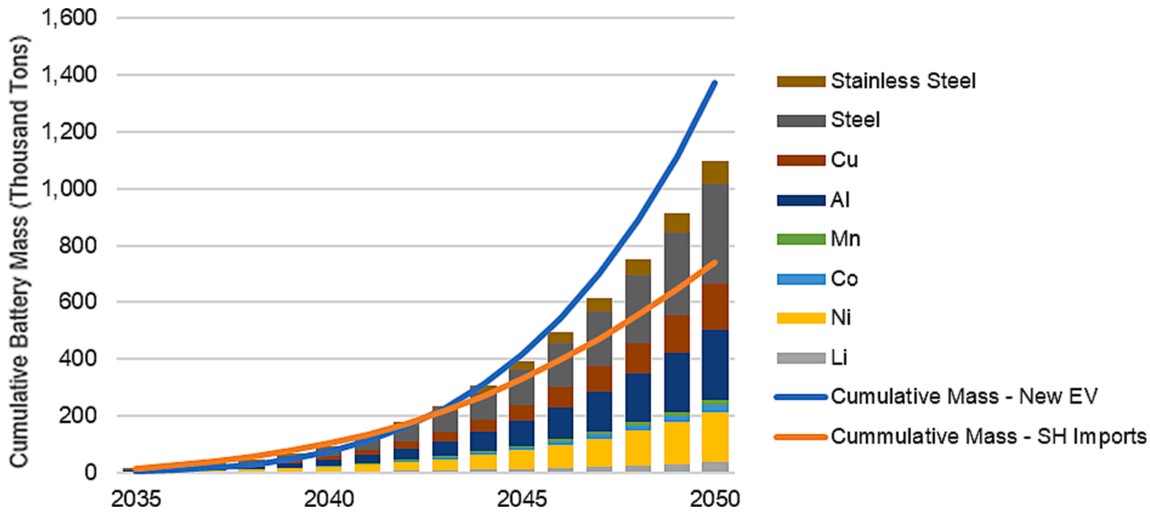

Fig. 8. Total cumulative battery mass (thousand metric tons) from deregistered SH Imports and new EVs sold in Mexico, including breakdown of recoverable battery materials from total cumulative deregistered EVs in Mexico (SH imports and new EV sales), from 2035 to 2050.

3.2.4. Deregistered EV battery material flow in Mexico

Fig. 8 displays the total cumulative mass of batteries from deregistered EVs in Mexico from 2035 to 2050 in contrast with the total mass of valuable recyclable materials from the batteries. The total battery mass for both, new EVs sold in Mexico and SH imports, increases significantly from a combined total of 19,000 metric tons (tons) in 2035 to 2,115,000 tons in 2050, indicating a sharp increase in the number of EVs on the road and consequently being deregistered in Mexico over the years.

Steel has the largest contribution among all the recyclable materials, with a mass of 3,000 tons in 2035 and 348,000 tons in 2050. Copper, aluminum, and nickel will also represent a significant proportion of the available materials with 162,000, 250,000, and 175,000 tons by 2050, respectively.

While the contribution of lithium, cobalt, and manganese to the total cumulative recoverable mass by 2050 is relatively small, at 35,000, 28,000, and 15,000 tons, respectively, their importance and value are significant due to their critical nature and scarcity.

It is important to note that the difference between the total cumulative battery pack mass and the recoverable material breakdown is explained by less valuable materials that BatPaC v5.0 does not include, such as the coolant, BMS electronics, polymer pads, pack insulation, pack heaters, and other less valuable materials.

4. Discussion

Vehicle imports to receiving countries depend on several factors including regulatory environments and incentives, macroeconomic fluctuations, public perception, and most prominently the availability of technology and the infrastructure to support it. In this sense, national adoption of new EVs and infrastructure in receiving countries will enable the creation of a SH EV market and drive its development.

Given the outstanding volumes of trade enabled by NAFTA, as well as the historic and geographic proximity, we have focused on the specific dynamics between the US and Mexico, and the risk of imposing environmental harms via the export of SH EVs. The modeling also provides an understanding how SH EVs will shape regional flows of critical materials used in batteries. Understanding the dynamics of the SH vehicle market and actively addressing the technical and regulatory gaps through a regional lens is critical to ensuring a successful and just transition towards a low-carbon transportation.

Our results indicate that while less so than in the initial period of legal SH imports between 2005 and 2010, when the ratio of SH imports to new vehicle registrations in the country was extraordinarily high, SH imports will continue to be a significant source of material input and a potential environmental concern for the country if not managed properly. Also, we see that as EV adoption in the region continues to rise and the fleet begins to age, EVs will begin entering the SH vehicle market at an accelerated rate within the next decade and consequently also will lithium-ion batteries.

SH EVs, however, will not be the most significant source of lithium-ion batteries in Mexico as total cumulative new EV sales from 2016 to 2050 will be close to seven times that of SH imports if Mexico's stated policy targets are met. Combined, these two flows will gradually change the composition of the vehicle fleet to the point where close to 50 % of vehicles on the road in Mexico will be EVs by 2050. An interesting and potentially impactful effect of this transformation is the significant reduction of the lifespan of vehicles, thus decreasing the entire fleet age to a mean of 10 years by 2050. While historically, Mexico has relied on the ability to repair vehicles and maintain them on the road for over 20 years, in some cases up to 30, the introduction of EVs will reduce the average vehicle deregistration age closer to 15 years old if vehicles are deregistered when their batteries are expected to no longer be serviceable in a vehicle. While this effect could foreseeably have positive environmental effects, particularly for air quality, it could become a transportation reliability issue for communities and could signify an increased burden for EOL management systems in the country.

Finally, our modeling sheds light on an interesting opportunity for Mexico that can arise from the increase in regional EV adoption: Battery recycling. In Fig. 8 we highlight the metric tons of battery pack materials entering the country yearly and, while steel appears to take the largest share of recoverable materials, more valuable metals like nickel, aluminum and copper also contribute to the total cumulative value significantly. While lithium, cobalt, and manganese contribute to a relatively smaller share of the total mass, their recovery and recycling remain critical for several two reasons. First, it helps to reduce environmental impacts by reducing the need for extraction from primary sources and avoids landfilling. Second, it ensures a stable and sustainable supply chain of critical minerals that are essential to produce EVs and other high-tech products. The relative scarcity of these critical minerals makes them more valuable per unit of mass than the more widely used metals, such as steel and copper.

5. Conclusions and policy implications

To minimize environmental burdens and maximize benefits for the entire region, EV adoption in the U.S. – Mexico – Canada Agreement (USMCA) region requires the development of EOL management strategies for both exporting and importing countries of SH vehicles. It is crucial for the United States and Canada, as exporters of used vehicles, to establish policies that promote circularity within their territories and ensure responsible export and EOL management. Simultaneously, Mexico, as the primary importer, must prioritize strategies to address the challenges posed by the projected volume of SH EV imports. We have summarized recommendations into the following three categories: exporting country opportunities, importing country opportunities, and joint actions.

5.1. Exporting country opportunities

The United States and Canada could collaborate to support battery recycling program development with Mexico, establishing and strengthening a regional North American battery recycling supply chain. This could facilitate the return and re-use of critical minerals to battery producing countries, securing the supply chain for EV battery manufacturing while providing economic and environmental benefits to countries that import SH vehicles.

Moreover, a regional extended producer responsibility (EPR) (Saidani et al., 2019) system among USMCA car manufacturers could be established. Depending on how responsibility is assigned, this approach could incentivize manufacturers to design systems through a lens of sustainability and EOL material recovery and recycling.

5.2. Importing country opportunities

Mexico could develop policies addressing the challenges of the growing volume of SH EV imports. These policies should include mandatory state of health (SOH) checks or other relevant battery life diagnostics on used batteries to prevent the import of vehicles with compromised batteries.

Mexico could also collaborate with nations that have established EV circularity policies such as the European Union's (EU) circular battery economy approach (Melin et al., 2021; Yu et al., 2022). The EU's approach is comprehensive and involves assigning responsible parties for battery EOL management, requiring recycling as the final disposal step, establishing recycled content standards for new battery manufacturing, and creating mechanisms to encourage second-life applications for used batteries in stationary energy storage or backup power systems while the ensuring quality and safety of these systems. Mexico could learn from these policies to create its battery circularity policies.

By exploring incentives, Mexico can strengthen local infrastructure or attract recycling companies to establish local operations, thereby creating a robust recycling infrastructure capable of managing EOL LIBs, benefiting from the high demand for critical minerals by creating jobs and contributing to the local economy.

5.3. Joint actions

Joint actions for the USMCA region should involve establishing a digital battery information protocol and shared database platform akin to the EU's Digital Battery Passport (European Comission, 2020). This could enable efficient tracking of EVs and their battery life cycle and foster greater transparency and accountability in the management of EOL EVs and their batteries and could support policies that require minimum SOH for SH vehicle imports and exports. Greater regional collaborations between customs agencies to unify and streamline trade registrations could simplify the export process, ensure compliance with regulations, and facilitate tracking SH EVs crossing the border. Especially given that current data on SH vehicle exports from the US show enormous underestimates of SH vehicle registrations recorded by Mexico.

Additionally, advocating for legislation supporting the right-to-repair EVs (aftermarketNews, 2021; ILT, 2020) could empower consumers and independent repair shops to maintain and prolong the lifespan of SH EVs, thus conserving resources and reducing the burden on recycling infrastructure downstream.

In conclusion, as EV adoption grows in the USMCA region, it is essential for exporting and importing countries to develop and implement effective EOL management strategies for EVs and their batteries. By learning from the experiences of early adopter countries like Sri Lanka and Mongolia, Mexico can benefit from the EV transition while ensuring responsible EOL management of EVs and batteries in collaboration with the United States and Canada.

6. Glossary

- **ANAM:** Agencia Nacional de Aduanas de Mexico (Mexico's National Customs Agency)
- **BatPaC:** Battery Performance and Cost Model
- **DOF:** Diario Oficial de la Federación (Official journal of the Mexican government where new laws, regulations, and other official communications are published)
- **EOL:** End-of-life
- **EPR**: Extended Producer Responsibility
- **EV:** Electric vehicle
- **GHG:** Greenhouse gases
- **GIZ:** German Corporation for International Cooperation
- **HEV:** Hybrid electric vehicles
- **ICCT**: International Council on Clean Transportation
- **ICEV**: Internal combustion engine vehicle
- **IEA**: International Energy Agency
- **ILT**: Human Environment and Transport Inspectorate (in the Netherlands)
- **INEGI**: Instituto Nacional de Estadística y Geografía (National Institute for Statistics and Geography of Mexico)
- **LDV**: Light-duty vehicle
- **LFP**: Lithium Iron Phosphate
- **LMICs**: Lower- and middle-income countries
- **MAE**: Mean Absolute Error
- **MAPE**: Mean Absolute Percentage Error
- **MoMo**: Mobility Model
- **NAFTA**: North American Free Trade Agreement
- **NCA**: Lithium Nickel Cobalt Aluminum Oxide
- **NGOs**: Non-governmental organizations
- **NEMS**: National Electric Mobility Strategy
- **NMC**: Lithium Nickel Manganese Cobalt Oxide
- **PHEV**: Plug-in hybrid electric vehicle
- **RSE**: Residual Standard Error
- **SEGOB**: Secretaría de Gobernación (Ministry of the Interior of Mexico)
- **SH**: Second-hand
- **SOH**: State of Health
- **TraCS**: Advancing Transport Climate Strategies
- **UN**: United Nations
- **UNEP**: United Nations Environment Programme
- **USMCA**: United States, Mexico, Canada Agreement

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2023.103934.

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