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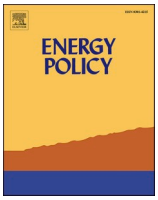

Transport poverty indicators: A new framework based on the household budget survey

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ABSTRACT

The energy transition represents an economic opportunity in many countries, but it can also disproportionately affect vulnerable households. Although increasing attention has been paid on energy poverty at homes, there is another dimension in which research has not yet placed enough emphasis: Transport poverty. This study proposes a framework for measuring transport poverty that uses information from the Household Budget Survey (HBS), a standardized database that is available every year in many countries. We develop and test 3 indicators that cover the affordability dimension of transport poverty (10%, 2 M, LHIC) and another one that also includes the accessibility dimension (VTU). Our research is supplemented by a statistical analysis that enables us to identify the drivers of transport poverty and by an analysis of the advantages and disadvantages of each metric. This framework offers a new common base for measuring transport poverty in different regions and enables transport poverty to be tracked over time.

1. Introduction

Reducing greenhouse gas emissions at the speed and scale needed to achieve the Paris Agreement goals will require a profound transformation of the energy system (Rama et al., 2022). To be successful the energy transition needs to be (and to be perceived as) socially fair and equitable for most of the population. Although the energy transition represents an opportunity in terms of net job creation for fossil fuel importing countries (Markandya et al., 2016; OECD, 2017), it can also disproportionately affect vulnerable households (Feindt et al., 2021). If policies aimed at increasing the cost of fossil fuels (e.g. carbon pricing) do not adequately factor in equity concerns, they might negatively affect low-income households (Böhringer et al., 2022; Tomás et al., 2023), thus aggravating existing inequalities (OECD, 2011; Piketty and Saez, 2014). Vulnerable households have more difficulties in taking advantage of the opportunities from the energy transition due to lack of access to finance, information or infrastructures, and this could undermine the public acceptability of climate mitigation policies (Maestre-Andrés et al., 2019).

There is a growing literature that begins to point out the importance of designing compensation policies or redistributive policies if we want to accelerate the energy transition (Carley and Konisky, 2020). The speed of the energy transition will be determined not only by technological, economic or financial factors, but also by social factors. An example of this is the "yellow vests" movement in France (Nature, 2018) following the increase in taxes on transport fuels. Therefore, many countries are now promoting "just transition" policies that can provide support to vulnerable groups in the transition to a net-zero carbon society.

In recent years, academic literature has placed increasing attention on energy poverty (Adom et al., 2021; Adusah-Poku and Takeuchi, 2019; Bednar and Reames, 2020; Castaño-Rosa et al., 2019; Dong et al., 2021; Halkos and Gkampoura, 2021), a situation in which households are unable to access essential energy services and products in their homes in both developed (Middlemiss, 2022) and developing countries (González-Eguino, 2015). This research has led to the emergence of new indicators that have proved very useful for tracking energy poverty and for designing policies aimed at protecting the most vulnerable groups, such as subsidies on electricity or heating fuels for low-income households. However, there is another dimension of energy poverty on which research has not yet placed enough emphasis: Transport poverty, i.e. the poverty associated with transport or mobility (European Commission, 2021; Martiskainen et al., 2021). In fact, transport poverty is increasingly relevant due to several factors. In the first place, a significant part

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of the energy bill of a household goes into transportation. Indeed, in the EU-27 an average of 49.5% of the total household energy bill is spent on fuel or transport services. Second, although energy poverty is critical (since it affects very basic needs at home), transport poverty can also have serious implications as it can limit access to other basic needs such as education, work, health and full participation in society. Third, emissions from road transport have continued to grow in the last few decades, so fiscal or regulatory policies will be increasingly aimed at tackling decarbonisation in this sector.

There is an emerging literature (Berry et al., 2016; Carruthers et al., 2005; Dodson and Sipe, 2007; Lovelace and Philips, 2014; Lucas et al., 2016; Mattioli et al., 2016, 2018; Tao et al., 2020) that proposes and analyzes indicators for transport poverty, but further progress is needed in this area. Many of the indicators proposed to date contribute to addressing transport poverty in specific contexts but share a key limitation: this studies depend on the collection of large amounts of information based on specific surveys (Salon and Gulyani, 2010) or field work for specific areas (Carruthers et al., 2005), which require substantial effort and limit their regular implementation and extension to broader areas such as an entire country or comparison between countries.

In this paper we propose a framework of transport poverty indicators that benefits from existing information drawn from the Household Budget Survey (HBS), a common statistic in all countries which is increasingly standardized and which has relevant potential due the large amount of socioeconomic information that it collects. We propose and analyze 3 indicators similar to those already used for energy poverty, focusing on affordability (10%, 2 M, LHIC), i.e. the economic effort that households have to make to cover their transport needs, plus a further new indicator (VTU) that enables aspects related to accessibility of public transport to be factored in. This framework and these metrics are applied here for the case of Spain using a compilation of HBSs from 2006 to 2021. The study shows the trend over time of the proposed indicators and the potential of the large amount of microdata contained in HBS for a very detailed analysis of transport poverty for different sociodemographic groups (e.g. rural households).

Our study makes also a timely contribution to the literature in a context where EU Member States are required to consider measures to combat transport poverty (e.g. Social Climate Plans, European Commission, 2021) but there is a lack of common definitions and indicators. For example, the Social Climate Fund aims to channel resources to the most vulnerable groups, including vulnerable transport users. Therefore, our study can help conceptualize transport poverty and define common indicators capable of identifying vulnerable transport users. Thus, future policy measures aimed at protecting vulnerable transport users can focus on the households identified in the framework proposed in this paper.

Moreover, our framework can be also useful for other, non-EU countries as most of them already have HBSs and there is a growing effort to try to make such surveys more standardized. In the case of the EU-27, for example, there is already a standardized HBS that enables comparisons to be drawn between countries, and the World Bank has the same objective for many other countries around the world (Oseni et al., 2021).). Of course, these indicators based on HBS have their own advantages and limitations, which are also assessed here.

In summary, the main objective of this study is to provide a framework that allows monitoring transport poverty and show its application to the case of Spain. We hope that this work can be used in the future in other countries and also to design compensation policies that allow accelerating the energy transition also in the transport sector.

The paper is structured as follows: Section 2 reviews the literature on transport poverty. Section 3 describes the new framework proposed based on the HBS dataset and presents four transport poverty indicators that can be drawn up based on it. Section 4 applies this framework to Spain, assesses trends from 2006 to 2021 and gauges the strength and weakness of each indicator. The study is supplemented by a statistical analysis on drivers that explain transport poverty. Finally, the limitations of the framework are also assessed. Section 5 summarizes the main conclusions of the study and suggests new areas for future research.

2. Literature review on transport poverty

Despite the efforts of some authors to define transport poverty, there is still no common, well-established definition of the term. Establishing a standard definition for transport poverty can be complicated for various reasons. Mobility is closely related to the provision of access to other goods, services and socioeconomic activities which are sometimes temporary and depend on the geographical context, making it difficult to define common transportation needs. It is also a condition whose effects are felt more at individual level, i.e. it can affect one member of a household and not the rest, with a very significant gender component (Booth et al., 2000; Robinson and Thagesen, 2017).

The paper by Wachs and Kumagai (1973) first presented access to employment and urban services as an important measure of quality of life, considering transportation accessibility as a measure of social and economic inequality. Later, the Social Exclusion Unit (Simpson, 2003) placed the issue of transport at the heart of the debate on social exclusion, as it is essential for access to education, work, healthcare and other essential activities for full participation in society.

Since these early studies, different terms have been used to refer to transport poverty, making for a lack of consistency in academic literature and policy. To overcome this problem Lucas et al. (2016) propose establishing a common lexicon for notions that help conceptualize transport poverty (see Table 1). Based on the notions described in Table 1, Lucas et al. (2016) develop a new, single definition for transport poverty, stating that an individual is in a situation of transport vulnerability if he/she meets any of the following conditions: i) Not having within his/her reach mobility options adapted to his/her capabilities or physical conditions, ii) Not being able to maintain a reasonable quality of life due to a lack of transportation options to enable him/her to get to places where he/she can carry out his/her daily activities, iii) Having with a residual income below the official poverty line due to a need for high expenditure to meet his/her mobility needs, iv) Having to invest excessive time in daily journeys, so that he/she is at risk of suffering from time poverty or social isolation; or v) Having to travel regularly in dangerous, unsafe or unhealthy conditions.

Table 1
Definitions of the notions to conceptualize transport poverty.

Notion	Definition
Transport affordability	This refers to households' ability to purchase the basic mobility needed to access essential activities such as education, work, shopping and healthcare (Litman, 2021). A household is vulnerable if it cannot afford transportation options, either public or private transport.
Mobility poverty	This is related to a systemic lack of transportation and mobility options, often connected to a lack of services or infrastructures (Lucas et al., 2016; Moore et al., 2013).
Accessibility poverty	This refers to the inability to reach key social or economic activities at reasonable time, ease and cost (Social Exclusion Unit, 2003) (Abley, 2010). Given that transportation is a necessary means to satisfy certain needs and make certain rights effective (Cebollada, 2006), accessibility poverty reproduces the general conditions of poverty and perpetuates social exclusion.
Exposure to transport externalities	Disproportionate negative exposure to the transport system, such as chronic diseases and deaths from traffic related pollution or road traffic casualties, are considered as another dimension of transport poverty in broader definitions (Barter, 1999; Booth et al., 2000; "Planning and Design for Sustainable Urban Mobility. pdf," n.d.)

Source: Adapted from Lucas et al. (2016).

Following the framework of Lucas et al. (2016) the different efforts to measure transport poverty in the last few decades can be characterized. Table 2 summarizes some of the studies and metrics that have been proposed in the literature to quantify the scope of transport poverty. Many of these indexes attempt to measure the extent of transport poverty, but most of them are complex and difficult to replicate over time, as they use very specific data collected for each study and specific national statistics that are not available in all countries. These specific measures may serve to provide a picture of the extent of transport poverty at a particular time and in a particular context, but they are not useful for monitoring transport poverty over time or for comparing different contexts (regions or countries), so they do not facilitate decision making by policymakers. Therefore, in this paper we continue the effort made in these previous analyses to propose a set of metrics that can measure transport vulnerability and that can be replicated over time and in different contexts using public databases that are usually collected by several countries, including consumer surveys such as the HBS.

3. Methodology: a new framework based on the HBS

This section presents a new framework, which is summarized in Fig. 1, for measuring transport poverty based on the Household Budget Survey. The HBS provides information on household spending on goods and services and very detailed information on certain demographic and socioeconomic characteristics of each household. The HBS is also carried out and standardized at European level, so the methodology is replicable and comparable in other European countries, but it is also conducted in non-EU countries all over the world (Oseni et al., 2021). Using this database makes it possible to calculate a number of potential indicators of transport poverty for a wide range of countries. Thus, using the HBS microdata as inputs, households vulnerable to transport are identified based on 4 complementary criteria. Each criteria is related to one or more dimensions of transport poverty and uses different thresholds (expenditure and income) to identify transport poor households. The criteria to identify vulnerable households range from less restrictive (10%, 2 M) to more restrictive (LIHC, VTU). Thus, the 10% and 2 M metrics identify households that are vulnerable to changes in the prices of transport goods and services, and the LIHC and VTU metrics identify severely vulnerable households, for whom transport can aggravate their situation of overall poverty. Once vulnerable households have been identified, the scope of transport poverty can be shown in relative terms (percentage of households that are in a situation of transport poverty over the total population or percentage of households that are in a situation of transport poverty over the total of households that consume transport goods and services) or in absolute terms (total households or total people in a situation of transport poverty). In addition, metrics can be displayed for the total population or for a specific group of the population (taking into account various socioeconomic and demographic categories of households).

We seek to identify which of the proposed indicators are capable of systematically quantifying and identifying vulnerable transport users. In this sense, having a battery of transport poverty indicators is essential for policymakers to be able to monitor this problem, apply measures to end transport poverty, and design fairer policies that can help mitigate the potential adverse effects of policies aimed at accelerating the energy transition.

3.1. Data

To calculate transport poverty indexes, we use microdata from the Spanish HBS for 2006–2021 provided by the National Institute of Statistics (INE). The HBS has a representative sample of Spanish households each year made up of around 22,000 observations. Before transport poverty indexes can be calculated a number of adjustments must be made to the HBS microdata. Thus, certain socioeconomic and

Table 2
Transport poverty metrics.

	Metric	Description	Study
Affordability metrics	10%	A household is in transport poverty if it devotes more than 10% of its expenditure to personal or public transport.	RAC Foundation (2012)
		An individual is in transport poverty if he/she is spending more than 10% of his/her income on work travel.	Lovelace and Philips (2014)
	Low Income High Cost metric of car-related economic stress (CRES)	A household experiences car related economic stress if the % of income spent on running motor vehicles is more than twice the median share of income spent on running motor vehicles in the first year of the dataset (9.5%) and if its equalized income after housing and running motor vehicles costs is below 60% of the median.	Mattioli et al. (2016) Mattioli et al. (2018)
	Forced Car Ownership (FCO)	To be classed as being in FCO households must meet 2 conditions: i) owning at least one car and ii) being materially deprived, i.e. reporting difficulties in affording rent, mortgage, household maintenance, energy bills or food.	Mattioli (2017)
	Public Transport Affordability Index	This refers to the % of income needed to undertake sixty 10 km one-way trips per month on public transport. To calculate the affordability index the authors use the following data: i) income level in each area; ii) quantity of travel; and iii) fares in those areas.	Carruthers et al. (2005)
	Vulnerability Index for Petrol Expense Rises (VIPER)	The study proposes an approach that enables vulnerability of households to fuel price spikes to be measured at the local suburban scale. The index is constructed from 3 variables from the Australian Census: i) socioeconomic index for areas; ii) household motor vehicle ownership; and iii) car	Dodson and Sipe (2007)

(continued on next page)

Table 2 (*continued*)

	Metric	Description	Study
		dependence for the journey to work.	
Mobility poverty metrics	Travel choices	The authors use a survey to identify and analyze residents who cannot afford any of the motorized transport options available, identifying numerous barriers that limit mobility options, especially for women and children.	Salon and Gulyani (2010)
	Activity space	The study uses 4 indicators to capture the spatial extent and diversity of activity space: i) standard distance circle (SDC); ii) total distance travelled (TDT); iii) number of geographic locations visited (NGL); and iv) number of unique activity places (NAP).	Tao et al. (2020)
Accessibility metrics	Accessibility index	The study calculates accessibility based on employment opportunities at a given destination. The equation for estimating accessibility is made up of the following variables: i) number of relevant opportunities at the place of destination; ii) travel time, distance or cost for a trip between 2 locations; iii) the impedance function measuring the spatial separation between 2 locations.	Shen (1998)
	Synthetic index of adequate service	This study proposes an index on geo-referenced information for measuring access by the urban poor to public transport in Brazil. It comprises: average monthly expenditure on transport; walking distance to nearest bus stop, average headway, average travelling time, reliability of service, capacity, security and safety.	Gomide et al. (2005)
	Transport disadvantage	The study uses secondary data analysis and a quantitative household survey to study transport accessibility, and how the lack of public transport	Currie et al. (2010)

Table 2 (*continued*)

	Metric	Description	Study
		options impacts households.	
	Rural activity spaces	This study measures activity spaces for 157 individuals for weekdays, weekends, and for a week using weekly activity–travel diaries and focus groups to explain the differences between different socio-spatial groups	Kamruzzaman and Hine (2012)
	Overall measure of accessibility of services	The accessibility index is calculated by indexing and weighting the average minimum travel times to key services (education, healthcare, shopping, etc.) for each area.	Department for Environment, Food and Rural Affairs (2019)
	Transit access to employment	This study measures and analyzes vertical inequalities in access to employment to estimate how many, where, and to what extent individuals are at risk of transport poverty. For this, the authors use competitive access to employment equations to calculate: i) measure of a locations access by transit; ii) measure of a locations access by car; and iii) the number of workers in a catchment area for a given work location.	Allen and Farber (2019)
	Spatial Accessibility Poverty (SAP) indices	The study proposes two methods (tailored for rural areas in the Global South) for measuring transport-related exclusion in rural areas caused by lack of access to basic opportunities. The authors propose gravity-based models based on travel impedance methods derived from i) Friction surface datasets; and ii) Kernel density maps.	Benevenuto and Caulfield (2020)
Composite metrics	Composite risk of transport poverty index	Comprised of: "1) households that would need to spend 10% or more of their income on car running costs 2) people living more than one mile from nearest bus or station; 3) number of essential services that it would take more than 1 h to access by	Sustrans (2012)

(*continued on next page*)

Table 2 (*continued*)

	Metric	Description	Study
		walking, cycling and public transport".	
	Composite indicator of vulnerability	The study seeks to identify households that run the risk of facing difficulties if fuel prices increase by proposing a composite indicator of vulnerability including financial resources, mobility practices and conditions of mobility.	Berry et al. (2016)

Source: Adapted from Lowans et al. (2021).

(UC2).[1] The medians for the calculation of the indices are calculated based on the expenditure of households that consume transport goods and services, excluding those that do not have transport expenditure.

3.2. Transport poverty metrics

3.2.1. Affordability measures

After presenting the conceptual framework in the previous section, we focus first on affordability metrics, since it is very difficult for a single measure to cover all the vulnerability perspectives listed in Table 1. It is important to analyze all perspectives of transport poverty, but we focus on transport affordability because it has the following advantages: 1) The data required to calculate the indexes are already available in existing statistics and are easily accessible; 2) The indexes can be calculated for a wide time series; and 3) The indexes are replicable and comparable for all Member States of the European Union.

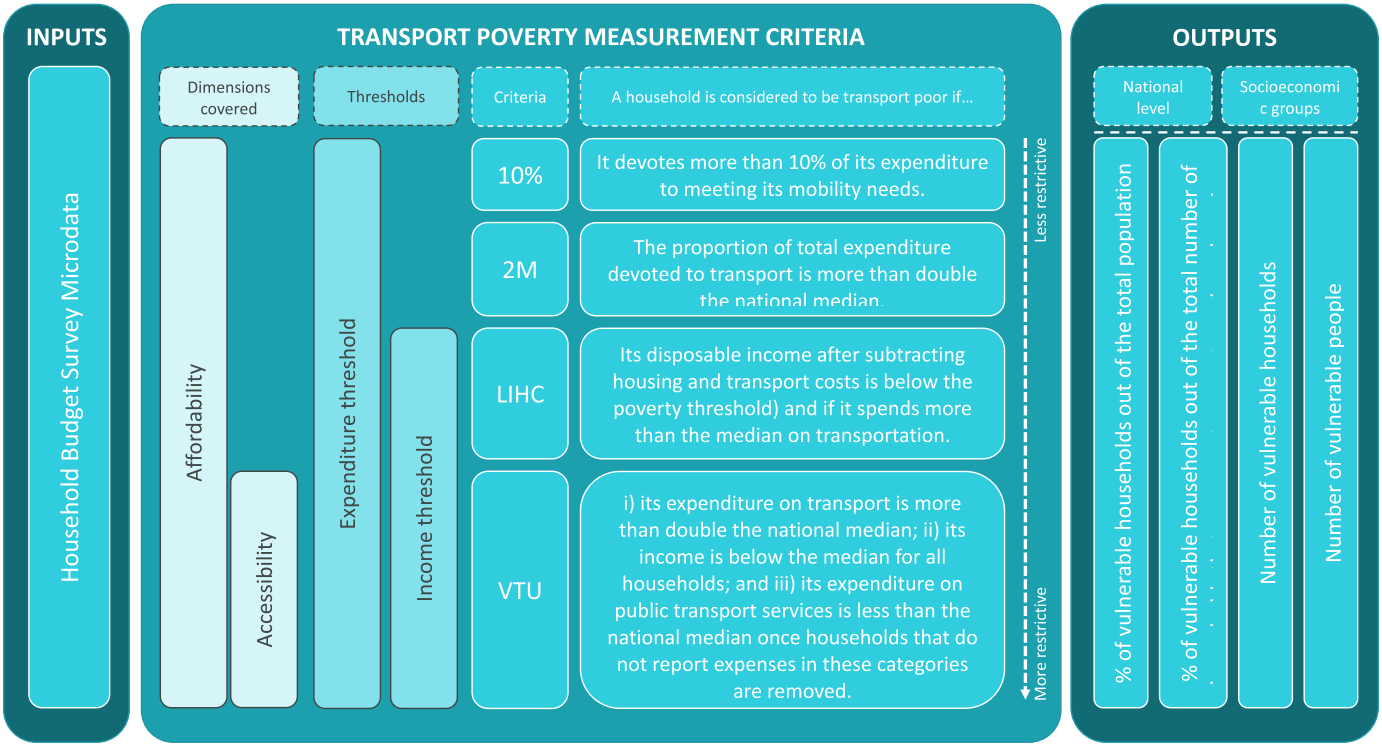

Fig. 1. Summary of the new framework to measure transport poverty.

demographic variables have been created and renamed (see Table A1). We calculate a new variable of transport expenditure taking into account spending on goods and services related to private transport (fuels) and to short and medium-distance public transport (bus, metro, commuter train, etc.). Table A2 shows the expenses reported in the HBS that are included as transportation expenses for the calculation of the metrics. We also separately calculate the total expenditure on private transport (sum of the categories listed in Table A2 under the heading of private transport) and public transport (sum of the categories listed in Table A2 under the heading of transport services). Transportation spending and total spending are corrected via the Equivalent Consumption Unit

Thus, we propose 3 metrics that may be useful for policymakers in monitoring vulnerability to transport poverty. These metrics are adapted from those widely used to quantify energy poverty (Siksnelyte-Butkiene et al., 2021), as they also measure the extent to which households can afford the energy that they need. It should be noted that some of them, such as the 10% rule and the LIHC, have already been explored in the context of measuring transport poverty (Lovelace and Philips, 2014; Mattioli et al., 2018, 2016; RAC Foundation, 2012). However, they have been calculated using specific databases that do not allow comparison with other EU Member States and to date there is no comparative analysis that includes them all at the same time.

[1] The UC2 is the OECD's modified equivalence scale used to take into account the economies of scale generated in households based on their size. The modified OECD scale values the reference person in the household at 1, the rest of the members aged 14 or over at 0.5, and the rest of the members under 14 at 0.3.

- **10% rule.** A household is classed as transport-vulnerable if it devotes more than 10% of its expenditure to meeting its mobility needs. Expenditure on transport is understood as spending on both private transport and short or medium-distance public transport services (see Table A2).
- **Twice the national median (2M).** A household is considered to be transport-vulnerable if the proportion of total expenditure devoted to transport is more than double the national median. In other words, these are households whose socioeconomic situation leads them to spend disproportionately to maintain a level of mobility appropriate to their needs. Expenditure on transportation is made up of the goods and services included in Table A2. The full sample is used to calculate the index, but to calculate the median expenditure we eliminate households that do not consume transportation goods or services, i.e. we calculate the median expenditure of households that spend money to meet their mobility needs.
- **Low Income High Cost metric (LIHC).** A household is classed as vulnerable to transport poverty if its disposable income after subtracting housing and transport costs is below the poverty threshold (which in Spain is set at 60% of the national median) and if it spends more than the median on transportation.[2] As in the 2 M index, expenditure on transportation is made up of the goods and services included in Table A2 and the median used is that which applies to households that consume transportation goods or services.

3.2.2. *Affordability and accessibility metric*

To broaden the cover provided by the above measures, we also propose a composite indicator in which we seek to identify those households which are not only vulnerable to price increases in transport goods and services (affordability dimension) but also have no accessible alternatives to enable them to change their consumption patterns towards more sustainable mobility models (accessibility dimension). This indicator, defined as Vulnerable Transport User (VTU), identifies households that: i) have disproportionate expenditure on private transport and transport services; ii) suffer from an unfavorable economic situation that makes investments in energy efficiency or in new carbon neutral technologies difficult; and iii) do not have accessible, affordable transport alternatives in a reasonable time. Therefore, according to this index, a household is considered a VTU if it meets the next three conditions at the same time: i) its expenditure on transport is more than double the national median; ii) its income is below the median for all households; and iii) its expenditure on public transport services is less than the national median once households that do not report expenses in these categories are removed. Finally, Appendix B provides further information on the equations used to calculate each metric.

To define whether a household has access to transportation, we need to know where it is located and what public transport is available there. This information is not usually available in any national survey for reasons of anonymity. Therefore, to include the accessibility dimension we use expenditure on public transport as a proxy. Hence, we assume that those households that spend small amounts on public transport do not have access to public transport services or that the public transport available does not cover their mobility needs. We believe that this may be a good proxy since the data confirms that households in areas where public transport is less accessible, such as sparsely populated and rural areas (Porru et al., 2020; Šťastná and Vaishar, 2017; Tomej and Liburd, 2020), spend a proportionally lower percentage of their income on public transport services and a higher percentage on fuels for private transportation (see Table 3).

4. Results and discussion

4.1. *The trend in transport poverty in Spain*

The proposed indexes have the advantage that they can be calculated annually, which makes it possible to analyze the trend in transport vulnerability over time. Analysing the evolution of transport poverty is very relevant for policymakers since they could see if the measures applied have allowed them to alleviate transport poverty. Fig. 2 shows the percentage of households in a situation of transport poverty for 2006–2021. In Spain, except for the 10% index, transport poverty rates followed a similar, slightly upward trend until 2011–2014 then, depending on the measure, a slight decrease until 2018. For the period up to 2014, rising energy prices from 2006 onwards (by 2012 they were 49% higher than in 2006),[3] coupled with falling incomes and rising inequality due to the 2008 economic crisis, are behind the increasing trend across the whole index. This trend is corrected with the post-crisis recovery, especially in the LIHC and 2 M indexes. Finally, since 2020 there has been a greater decrease in all measures due to the COVID-19 pandemic, which led to an abrupt decrease in mobility and therefore in consumption, but also brought about an unprecedented reduction in fuel prices for private transport, only comparable to the one that occurred in 2008–2009. In fact, the number of households that consumed transport goods or services fell by almost 14 percentage points (from 69.4% in 2019 to 55.8% in 2020).

By contrast, the 10% index shows more notable changes, for both households as a whole and consumers of transportation services (Fig. 3), with more abrupt rises and falls. The main driver behind the trend in this index can be found in fuel prices, since the trend throughout the historical series coincides with the trend followed by fuel prices.[4] Households do not easily change their transport consumption (Labandeira et al., 2017), so the higher fuel prices become, the greater the share of income devoted to fuel and thus the 10% index, and vice versa when prices fall.

Fig. 3 depicts the percentage of households that consume transport goods and services which are in a situation of transport poverty. As expected, these rates are higher than those calculated for the total

Table 3
Consumption structure of Spanish households as regards transport goods and services in 2019.

Density of the municipality of residence of the household	% of income allocated to transportation (total)	% of income allocated to private transport	% of income allocated to public transport
Densely populated area	3.9%	3.2%	0.7%
Intermediate area	4.7%	4.3%	0.4%
Sparsely populated area	5.3%	5.1%	0.3%
Total	4.4%	3.9%	0.5%

Source: Own elaboration based on HBS data

[2] The poverty threshold is calculated as 60% of the median annual income per consumption unit (or equivalent income) of all households nationwide. This is the standard way of measuring relative poverty in the EU and in the OECD and is thus defined by the National Institute of Statistics of Spain. This threshold has also been used repeatedly in the academic literature (Markova et al., 2021; Nelson, 2013; Palomino et al., 2020).

[3] Own calculation based on fuel consumer price indices data provided by INE.

[4] The transport expenditure threshold for the 10% metric is constant over the years (it is 10%), but for the other indicators the threshold varies depending on the national expenditure median for each year. Therefore, when transport expenditure is higher due to price increases, more households are more likely to expend more than 10% of their income on transport and to be poor according to the 10% metric. However, for the other indicators, when all household transport expenditure is higher due to prices, the threshold will also be higher and therefore they will not be as affected by price fluctuations.

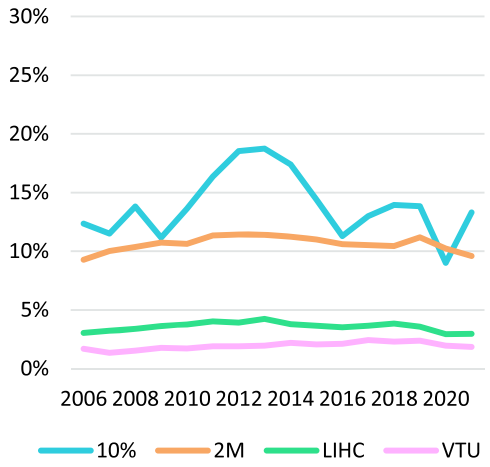

Fig. 2. Transport poverty indexes 2006–2021 (% of total Spanish households).

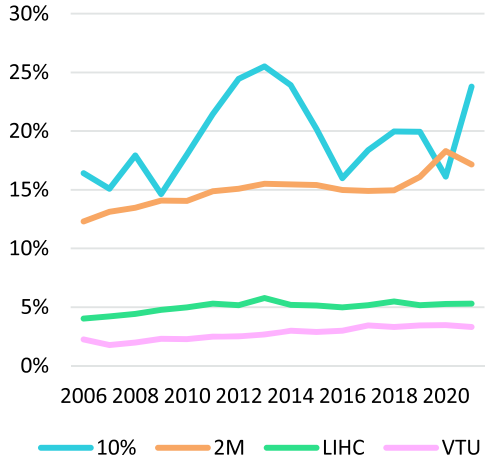

Fig. 3. Transport poverty indexes 2006–2021 (% of consumer households of transport goods and services).

number of households, since transportation poverty affects only households with transportation needs. Likewise, except in the case of the 10% index, the indexes continue to rise throughout the historical series. In particular, a significant increase in transport poverty has been observed in the last two years (for example, the 2 M metric goes from 16.1% in 2019 to 18.3% in 2020 and 17.2% in 2021) which contrasts with the results calculated for all households. This indicates that the percentage of households that consume transport goods and services significantly influences transport poverty indexes and that during the pandemic transport poverty indexes dropped for circumstantial reasons (reductions in both mobility and fuel prices) and not due to measures that promoted structural improvements.

4.2. The extent of transport poverty in Spain

This section analyzes the dimension of transport poverty in Spain. We focus on 2019 because the lockdown measures derived from the COVID-19 pandemic make 2020 and 2021 exceptional years within the historical series. Thus, Fig. 4 shows the distribution of the 22,000 Spanish households in our dataset according to their total expenditure and their expenditure on transport for the 4 measures described above for 2019.

First, it is observed that the 10% and 2 M indices have a broader focus and enable us to identify which households are particularly vulnerable to changes in the prices of transport goods and services, so that the socioeconomic circumstances of the moment will influence whether or not they fall into transport poverty. According to these measures between 2.1 M (2 M) and 2.6 M (10%) of households could be transport-vulnerable. This is equivalent to 5.9 M and 7.3 M people respectively (Table 4).

LIHC and VTU are more restrictive measures, as they also include income thresholds and thus identify those poor households that are also affected by transportation poverty. These measures make it possible to identify households that incur severe transport poverty because their socioeconomic or demographic characteristics mean that they find it harder to meet their transport needs and find alternative mobility solutions to reduce their dependence on private transport. These indexes give figures of 348,947 vulnerable households according to the VTU and 559,106 according to the LIHC, equivalent to 1.3 M and 1.8 M people respectively (Table 4). The VTU index shows fewer vulnerable households than the LIHC, as it also identifies households that have little access to public transportation.

4.3. Transport poverty indexes broken down by sociodemographic characteristics

Another advantage of using the microdata available in the HBS is the great granularity with which the results can be displayed and analyzed. This section analyzes the transport poverty indexes calculated based on different socioeconomic and demographic characteristics.[5] Calculating energy poverty indices for different socioeconomic groups is very valuable for policymakers as it helps to identify which groups are most affected by transport poverty and therefore strategies to alleviate transport poverty could be more focused on these groups.

4.3.1. Transport poverty per household income level

Fig. 5 shows the proportion of transport-poor households according to the different measures proposed per income decile, while Fig. 6 shows the vulnerable households according to transport users. Under the 10% and 2 M indexes the proportion of transport-vulnerable households is highest among the middle class (Fig. 5), while those calculated on the basis of transport users (Fig. 6) show, the households at the bottom of the income distribution to be the hardest hit. The latter follow a clear downward trend as household income increases. This difference in the trend is due to the fact that households in the lower deciles do not own motor vehicles and do not have frequent access to them (Dargay, 2001; University of Essex, 2021; Vidyattama et al., 2021): In decile 1 only 50% of households consume transport goods and services, but in decile 10 the figure is 83%. Thus, when all households (transport users and non-users) are included in the analysis, there is a lower proportion of transport-poor households in the lower income deciles under the 10% and 2 M measures. Likewise, households in the middle part of the income distribution are greater users of private transportation and devote a higher proportion of their income to transportation, so they are more highly represented in these measures. Households in the 5th income decile devote 5% of their consumer spending to transportation, compared to 3.7% among households in the upper part of the distribution and 3.9% in the lower part.

On the other hand, the LICH and VTU measures follow a similar distribution when all households are included in the analysis and when only transport users are considered. According to these measures the households hardest hit are those at the bottom of the income

[5] The indices by category are calculated by dividing the total number of vulnerable households in a specific group by the total number of households in that specific group or the total number of households in that specific group that spend on transport goods and services.

Fig. 4. Transport poverty indexes 2019 for Spain
Note: Equivalized transportation expenditure and equivalentized income are calculated by applying the OECD's modified equivalence scale (UC2).

Table 4
Transport Poverty Indexes 2017, 2019 and 2021.

Year	2017		2019		2021	
Index	Households	Individuals	Households	Individuals	Households	Individuals
10%	2,403,215	6,849,561	2,593,649	7,274,194	2,510,654	6,680,842
2 M	1,949,737	5,568,323	2,093,978	5,878,794	1,809,928	4,759,204
LIHC	674,179	1,926,369	670,521	1,840,232	559,106	1,453,887
VTU	448,698	1,326,284	446,424	1,327,287	348,947	1,046,299
Consumers[a]	13,083,180	35,952,499	13,004,944	35,856,385	10,549,090	29,747,866

[a] Number of households and individuals consuming transport goods and services in Spain.

distribution. As remarked above, these measures also include income thresholds, and thus identify poor households that are also vulnerable in term of transport. In the case of the LIHC there is a strikingly sharp increase from D1 to D2, mainly due to the fact that fewer transport users are concentrated in D1 since, as previously mentioned, households in the lowest deciles do not have access to or make frequent use of private vehicles, and the fact that they dedicate a lower proportion of their income to transportation expenses.

The fact that a large number of transport-poor households according to the 10% and 2 M indexes are in the upper deciles of the income distribution may seem contradictory if transport poverty is seen as just one more dimension of poverty (see Table 5). Thus, although these indexes help to identify the households hardest hit by increases in transport prices they can accumulate many false positives, i.e. households which are not really vulnerable. Measures that include an income threshold, such as VTU or LIHC, can help avoid this problem and identify households that are truly transport-vulnerable. Table 5 shows that the LIHC and VTU indexes eliminate false positives, as they do not identify any households in the highest income deciles as vulnerable.

4.3.2. *Transport poverty by household rurality levels*

There is a wide debate about the impact of the energy transition on rural households, since they have different energy needs and depend more on fuel for private transport (Creutzig et al., 2020; Robinson and Mattioli, 2020; Shammin et al., 2010; Tomás et al., 2020, 2021a; Wiedenhofer et al., 2013). To address the demographic challenge and design policies that help to ensure a just transition, it is therefore important to analyze territorial inequalities with regard to transport poverty. Fig. 7

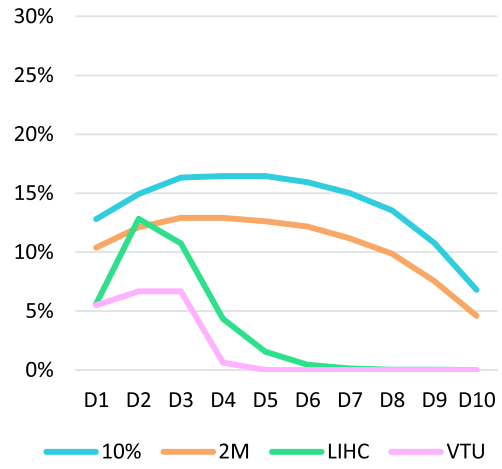

Fig. 5. Transport poverty indexes by decile for 2006–2021 (% of total Spanish households).

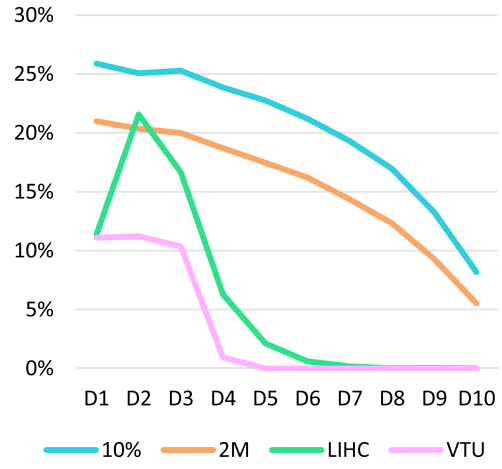

Fig. 6. Transport poverty indexes by decile for 2006–2021 (% of consumers of transport goods and services).

Table 5
Distribution of vulnerable households by deciles.

Decile	10%	2 M	LIHC	VTU	Consumers
1	8%	9%	13%	27%	7%
2	11%	11%	35%	33%	8%
3	12%	13%	31%	34%	9%
4	13%	13%	15%	5%	10%
5	12%	12%	4%	0%	10%
6	12%	13%	2%	0%	11%
7	10%	10%	0%	0%	11%
8	9%	8%	0%	0%	11%
9	7%	7%	0%	0%	11%
10	5%	4%	0%	0%	12%

and Fig. 8 show the distribution of transport-vulnerable households according the population density of the municipality where they are located.

As might be expected, all the measures used indicate that rural households (those in sparsely populated areas) are significantly more transport-vulnerable than urban households (those in densely populated areas). This can be explained by the greater mobility needs of people

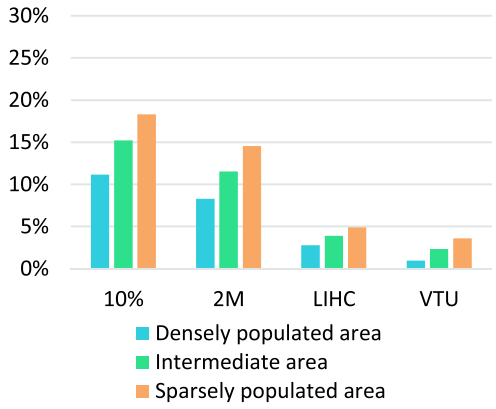

Fig. 7. Transport poverty indexes by population density of the municipality where the household is located for 2006–2021 (% of total Spanish households).

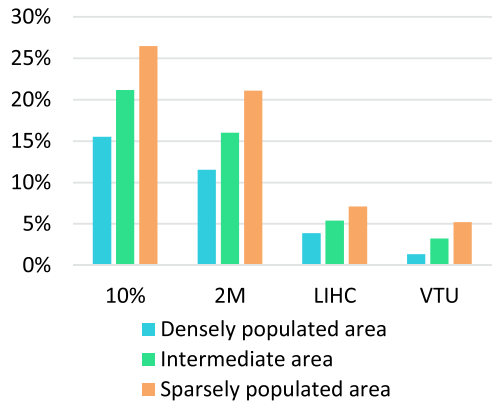

Fig. 8. Transport poverty indexes by population density of the municipality where the household is located for 2006–2021 (% of consumers of transport goods and services).

who live in rural areas and the lack of alternatives to private transportation. Fuel consumption for private transportation is significantly higher in rural households (5.1% compared to a national average of 3.9%). However, these consumption patterns are linked not only to greater mobility needs for daily activities on the part of people in rural areas but also, and fundamentally, to lack of access to public transport services (Székely and Novotný, 2022). This is decisive when analyzing transport poverty, since the lack of access makes it difficult for people residing in rural areas to participate on equal conditions in daily activities that enable them to fit into the society in which they live. All these factors could lead such households to a lack of mobility which is conducive to social disadvantage or even to social exclusion (Fransen et al., 2015). It is worth noting that VTU, which includes the affordability and accessibility dimensions, is the index that reports the greatest difference between urban and rural households. Thus, according to VTU the proportion of vulnerable households in rural municipalities is almost four times higher than in urban areas, and almost half of the vulnerable households identified under the VTU are in rural areas.

4.3.3. *Transport poverty per gender of the household reference person*

Gender is another relevant dimension in regard to transport poverty. Women depend to a greater extent on access to public transport, due to lower levels of private vehicle ownership (Cristaldi, 2005; Houillon, 2004; Cresswell & Uteng, 2016). Also, according to Markkanen & Anger-Kraavi (2019), the groups most exposed to the negative impacts

of climate change, including women, are also the most vulnerable to the adverse effects of poorly designed climate policies. Hence, the European Commission and other major international organizations emphasize the need to factor the gender perspective into public policies and to conduct gender impact analyses to improve the design of climate and energy policies. Fig. 9 shows the percentage of transport-vulnerable households for each measure analyzed according to the gender of their reference person.

First, it can be seen that under all the measures used households whose reference person is a man are more vulnerable to transport poverty than households whose reference person is a woman. However, if the analysis only includes transport users the difference between men and women narrows (see Fig. 10), since 76% of men but only 61% of women consume transport goods and services.

On the other hand, the index that reports the smallest difference between men and women is the LIHC. This is mainly because there is a greater concentration of women-headed households in the lower deciles of the distribution, while man-headed households are higher up in terms of income distribution. The fact that households headed by women are on average poorer than those headed by men puts women in a situation of greater vulnerability. Even so, men are identified by these indexes as harder hit by transport poverty because they are the main consumers of transport goods and services, and especially of fuel for private transport. On average, men dedicate 5% of their income to the consumption of transport goods and services (of which 4.5% is accounted for by fuel consumption) compared to 3.8% for women. These differences in consumption patterns are mainly explained by two factors: i) women have fewer mobility needs (e.g. commuting to work); and ii) women are more environmentally aware (and therefore use public transportation more) (Gordon et al., 1989; Guiliano, 1979; Hanson and Johnston, 1985; Luchs and Mooradian, 2012; Musova et al., 2021; Ng and Acker, 2018).

Nevertheless, when transport poverty is analyzed from a gender perspective, the question arises as to whether this type of poverty really affects households whose reference person is a woman less or whether these indexes fail to reflect reality because they do not take into account the gender gap in access to such goods and services. A measure capable of capturing "hidden transport poverty" could provide results that better reflect the reality of women regarding this issue. Further exploration is thus needed of the factors that condition the differentiated use by women of both private and public transport and the lower mobility of women, so as to really understand how the different realities experienced by men and women condition mobility, since this may be influential when it comes to making the principle of equal opportunities effective.

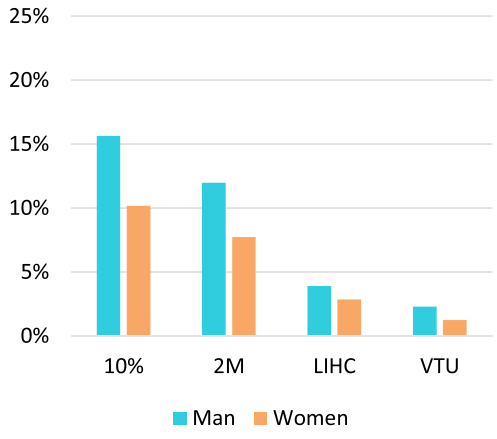

Fig. 9. Transport poverty indexes by genders 2006–2021 (% of total Spanish households).

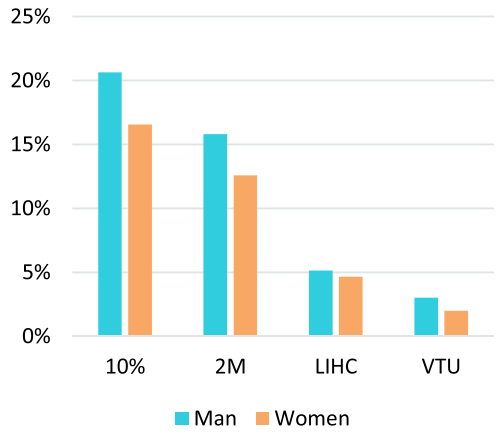

Fig. 10. Transport poverty indexes by genders 2006–2021 (% of consumers of transport goods and services).

4.3.3.1. Socioeconomic characteristics of the transport-vulnerable in Spain. Additionally, to identify the driving factors that explain the likelihood of suffering from transport vulnerability we estimate a logit model in accordance with some of the main socioeconomic characteristics of households (see Appendix C for methodological specifications). The aim of this analysis is to identify which are the main socioeconomic characteristics that may make a particular household severely vulnerable, considering "vulnerable" to mean those most likely to incur transport poverty. We consider households in transport poverty according to the LIHC and the VTU because these indicators are the least prone to give false positives (see Subsection 4.3.1.). Therefore, this analysis can be useful to design policies that focus on the most vulnerable groups at risk of transport poverty. Thus, Table 6 shows the coefficients estimated by the model for the LIHC and VTU indexes and the odds ratios, which indicate whether a type of household is more likely than the reference household chosen by the model (Table C1) to fall into a situation of vulnerability to transportation poverty (odds ratio greater than 1) or vice versa (odds ratio less than 1).

The results of the model provide an in-depth understanding of the socioeconomic and demographic factors that determine the likelihood of experiencing transport poverty. This is of particular interest to policymakers, since this information enables them to design specific actions focused on prioritizing the most vulnerable groups. Thus, according to the estimation in the model, the socioeconomic characteristics that most influence the likelihood of incurring transport poverty for both measures (LIHC and VTU) are: income, the size and population density of the municipality of residence, the sex and age of the reference person and the occupational status of the household.

As also shown in section 4.3., rural households and households whose reference person is man are more likely to experience transport poverty than urban and women-headed households, due to the different behavior and mobility needs of households by levels of rurality and gender. Moreover, households whose reference person is an adult are twice as likely to incur transport poverty as those whose reference person is young. Elderly people are also more likely than young people to be vulnerable, although not as much as adults. Adults have greater mobility needs than other age categories, especially to get to work, which explains why they suffer more from transport poverty. In the case of the elderly, vulnerability is mainly determined by income, since they are concentrated more in the lower part of the distribution.

The occupational status of households is also a determining factor. In this sense, it is observed that those households in which all individuals are employed are twice as likely (under the LIHC index) or almost three times as likely (under the VTU) to fall into transport poverty than those in which no-one is in work. The likelihood of households in which one

Table 6
Results for LIHC and VTU logit models.

	LIHC			VTU		
	Estimated coefficients		Odds ratio	Estimated coefficients		Odds ratio
Intercept	−3.5528	***	0.0286	−3.7727	***	0.0230
Income						
Equivalized total expenditure	−0.0002	***	0.9998	−0.0003	***	0.9997
Size of municipality of residence						
Small municipality	0.1862		1.2047	0.3240	**	1.3826
Pop. density of municipality of residence						
Intermediate area	0.3170	***	1.3730	0.7094	***	2.0328
Sparsely populated area	0.4319	***	1.5401	0.8022	***	2.2305
Gender of the household reference person						
Man	0.3225	***	1.3806	0.4026	***	1.4957
Education level of household reference person						
Primary education	0.4592	*	1.5828	0.3343		1.3969
Secondary education	0.6392	**	1.8950	0.4735	*	1.6056
Post-secondary education	0.5692	**	1.7668	0.2513		1.2857
Higher education	0.2841		1.3285	0.3787		1.4604
Age of household reference person						
Adult	0.7148	***	2.0438	0.7936	***	2.2114
Elderly	0.5069	**	1.6602	0.5794	*	1.7849
Country of birth of household reference person						
European Union	0.0864		1.0902	−0.2724		0.7616
Rest of Europe	−0.8401		0.4317	−2.6416		0.0712
Rest of world	0.0925		1.0969	−0.3741	**	0.6879
Occupational situation of household						
One employed	0.6798	***	1.9735	1.0483	***	2.8527
All employed	0.6991	***	2.0120	1.0668	***	2.9061
Not provided	1.0518	***	2.8629	1.1622	***	3.1969
Occupational status of household reference person						
Self-employed	0.4478		1.5649	0.6522		1.9197
Employee	0.7002	**	2.0141	0.8871	**	2.4281
Employer	0.4766		1.6106	0.7275		2.0699

Signif. codes: *** p < 0.01 ** p < 0.05 * p < 0.1.

person is employed is also much higher than that of households in which all members are unemployed, but slightly lower than that of households whose members are all employed. This is because most people in work have to commute to work and therefore have greater mobility needs, whereas the unemployed do not have a continuous need for mobility and may limit short journeys if they cannot afford them. Furthermore, in relation to the occupational status of the reference person, the model confirms that employees are more likely to be vulnerable to transportation poverty than the rest.

Regarding education levels, the LIHC metric indicates that households where the reference person has completed secondary, post-secondary or primary education are more likely to be transport-poor than those whose reference person has no education. This is mainly because they tend to be middle-class households with greater mobility needs. According to the VTU, the likelihood of incurring transport poverty at households where the reference person has completed secondary education is also higher than at those where the reference person has no educational qualifications.

The migration background of the household reference person can also influence the likelihood of incurring transport poverty. According to the VTU, households whose reference person was born in Spain are more likely to be transport-poor than those whose reference person was born in a country outside Europe. This indicates that the dimension of accessibility affects this type of household to a greater extent, because despite the fact that households with reference persons from other non-European countries tend to appear more in the lowest deciles of the distribution, they tend to be concentrated more in urban areas, where there is greater access to goods and transport services.

4.3.3.2. Comparative analysis of the proposed indexes. This section analyzes the main advantages and disadvantages of each index proposed in this study (see Table 7).

On the one hand, as mentioned above, most of the metrics proposed in the literature to capture transport poverty are difficult to reproduce as they depend on complex data collection processes and are thus hard to replicate and less useable for monitoring transport poverty over time. Some of the measures proposed in the literature also depend on qualitative variables of subjective measures, so it is difficult to use them as the core of an indicator system to track the trend in transport poverty. By contrast, the four indexes proposed here, based on the rich information from the HBS, can solve these problems, since they can be calculated for a wide time series and for a variety of countries. For example, for all the Member States of the EU-27 that use the standardized HBS provided annually by EUROSTAT and for other countries that use the HBS provided by the World Bank.

Also, although the 10% and 2 M indexes are easy to calculate, and to a certain extent to report (which could be why they are still used by governments for measuring energy poverty at home), their main disadvantage is that they overestimate transport poverty by showing numerous "false positives". As shown above, a large number of households identified as vulnerable according to the 10% and 2 M are in the top 50% of the income distribution. Transport poverty is a component of overall poverty, so wealthier households in the distribution should not be identified as transport-vulnerable. These shortcomings can be overcome with measures that introduce an income threshold such as the LIHC and VTU metrics, since they make it possible to identify households that, in addition to being poor, their situation of poverty is aggravated by the high percentage of income that they have to dedicate to satisfying their mobility needs.

In addition, 10% also has the disadvantage of being very sensitive to changes in fuel prices. Hence its great variability throughout the historical series. The variability of such indices is a drawback because poverty, although it may be aggravated by various cyclical factors, is considered a structural problem (Calnitsky, 2018; Royce, 2022). In fact,

Table 7
Advantages and disadvantages of the proposed transport poverty indexes.

	10%	2 M	LIHC	VTU
Advantages				
The data required is already available and accessible	x	x	x	x
It can be calculated for a wide time series	x	x	x	x
It is replicable and comparable for other countries or regions	x	x	x	x
It is objective and based on quantitative information	x	x	x	x
It can be easily interrelated with energy poverty indices	x	x	x	x
It is easy to calculate and communicate	x	x		
It identifies severely vulnerable households and minimizes false positives			x	x
It covers more than one transport vulnerability dimension				x
Disadvantages				
It is not able to cover all transport poverty dimensions	x	x	x	x
It does not measure hidden transport poverty	x	x	x	x
It does not take into account the gender gap in the data	x	x	x	x
It only covers the affordability dimension	x	x	x	
It suffers from false positives	x	x		
It is sensitive to changes in the number of transport users	x	x		
It lacks any reference to household income	x	x		
It is sensitive to changes in household income	x			
It is sensitive to changes in prices of transport goods and services	x			
It has an unjustified threshold	x			

this index collects a higher proportion of false positives when there is an increase in fuel prices.

Finally, the VTU index goes one step further than the other indexes proposed. The 10%, 2 M and LIHC indexes cover aspects related to transport poverty from an affordability dimension, but VTU also captures access to alternative mobility options via public transport. Of course, the VTU index has certain inherent limitations due to the information related to public transport expenditure from the HBS, which is used as a proxy for public transport access. This is the best proxy available but it is still an approximation with limitations.

On the other hand, the framework and indicators proposed here have certain limitations and disadvantages. The main disadvantage is that these indexes focus mainly on the affordability dimension of transport poverty. The VTU index also seeks to cover access to public alternatives, but it leaves out other vulnerability dimensions such as mobility poverty (i.e. lack of public and private transportation infrastructures, which is more relevant in developing regions) and exposure to transport externalities. Moreover, the indexes proposed do not include households that cannot cover their transport necessities due to inability to pay for them, which can lead to situations of social exclusion. This may be the case from a gender perspective, as the indexes do not cover the gender gap in access to private transport and may therefore underestimate women's vulnerability. Other measures capable of capturing "hidden transport poverty" could provide results that better reflect the reality of these socioeconomic groups. Therefore, this framework should be reinforced with the existing literature based on surveys and quantitative and qualitative information. An interesting future research line that might help to fill this gap could be to apply the literature based on statistical techniques to match surveys with different purposes but common information (Tomás et al., 2021b). For example, HBS could be matched with information from the Income and Living Condition Survey (a survey which is frequently provided by national statistical services) or the Time Use Survey in order to capture and combine more details on transport such whether or not people own private vehicles or how much time is used on commuting per type of household.

5. Conclusions and policy implications

In the context of the current energy crisis, with skyrocketing inflation especially in fuel prices, environmental justice and inequality are particularly important on the environmental policy agenda. It is therefore essential to identify what households and individuals are likely to be hit hardest by the energy transition so as to ensure a fair, equitable transition. The same goes for those affected by transport poverty. We propose for the first time a framework for measuring transport poverty that makes use of existing information from the Household Budget Survey (HBS), a rich source of data available in many countries. Therefore, our framework can be scaled up and used in different contexts and regions, and can enable transport poverty to be tracked over time, which could be especially useful for decision-making.

To that end, we develop 3 indicators that cover the affordability dimension of transport poverty and one that also offers for the first time an easily replicable composite measure for affordability and accessibility. Of those indicators, the 10% and 2 M indexes have a broader focus and can identify households that may incur transport poverty due to price impacts, but they can suffer from false positives. By contrast the LIHC and VTU indexes have the advantage of minimizing false positives, identifying severely vulnerable households that suffer from transportation poverty. Unlike the other 3 proposed indicators, the VTU not only assesses affordability but also seeks to introduce the accessibility dimension into the analysis.

The availability over time and high level of granularity of the data available for calculating these indices (HBS) not only makes them useful for analyzing the extent of transport poverty but also facilitates analysis of trends in the phenomenon throughout the historical series. They can also be used to identify the socioeconomic and demographic characteristics of vulnerable transport users. Therefore, analysis via these measures enables us to identify socioeconomic groups that require special attention if policies are to reduce transport poverty, such as low-income households and rural households.

Like any other indicator, these metrics also have their limitations. They do not include other dimensions of transport poverty, such as households that cannot cover their mobility needs due to inability to pay for them, which can lead to social exclusion. This may be the case from a gender perspective, as the indexes do not consider the gender gap in access to transport goods and services and may therefore underestimate women's vulnerability. Other measures capable of capturing "hidden transport poverty" could provide results that better reflect the reality of women and other vulnerable groups.

The new framework proposed in this paper may also have direct policy implications, especially in the framework of the "Fit for 55" package and the EU Social Climate Fund (SCF). As already mention, these policies aim to channel resources to the most vulnerable groups, among which vulnerable transport users stand out, to mitigate the possible social effects that the legislative reforms derived from the revision of the EU climate and energy framework could have. In fact, the main objective of the SCF is to achieve the decarbonisation of transport sector while offering the possibility to provide direct support to vulnerable households (European Commission, 2021), e.g. vulnerable transport users (as indicated in article 2 of the SCF proposal). However, as the European Parliament has recognized, there is no common definition of transport poverty and consequently no common methodology to identify and quantify vulnerable transport users (Art. 2(13)), which makes it difficult to channel support to the most vulnerable households. Our analysis and methodology can therefore help to improve policies at EU level in the coming years and inform which socio-economic groups should be supported in the energy transition. But also in the Spanish context this analysis may be relevant, as shown that during the period of amendments to the Sustainable Mobility Law, which is in parliamentary processing, a proposal has been presented to include the creation of a "National Strategy to end Transport Poverty", for whose development it will be essential to have a battery of indicators that allow monitoring its evolution, and to identify the most affected groups to effectively guide mitigation policies.

Moreover, our framework can also be useful for national policy makers, as the conceptualization of transport poverty and the use of common indicators for all Member States will make it possible to monitor the transport poverty situation and therefore also to assess possible impacts on these vulnerable households due to other energy policies. Likewise, many EU countries have introduced fuel subsidies to mitigate the effects of the energy crisis and inflation on the most vulnerable groups. These subsidies have benefited all consumers, regardless of their income level or degree of vulnerability. Therefore, the framework proposed here could facilitate the design of surgical aids to reach the most vulnerable groups to a greater extent, thereby freeing up the remaining resources that could be allocated to other policies promoting the decarbonisation of the transport sector. Thanks to our indicators, it would then be possible to design and implement more targeted progressive measures for vulnerable groups. In the same way that an electric and thermal social bonus exists, similar instruments can be explored in the field of transport to protect in the short term the most vulnerable people without alternatives to the private car in all Member States. In the medium term, as the VTU index highlights, the public transport network should be improved and active mobility should be facilitated to provide them with transport alternatives.

In short, these indexes are a good starting point for characterizing and analyzing transport poverty, and they can offer important, relevant information on the economic characteristics that make some households vulnerable to transport poverty. They can help policymakers to design policies to mitigate the adverse effects of rising prices of transport goods and services and to compensate vulnerable groups. Hence, this study makes a timely contribution to the literature in a context where EU

Member States are required to consider measures against transport poverty but there is a lack of a common definition and indicators. Moreover, the VTU measure proposed here is a relevant approach for further research that can be applied elsewhere, as it is able to cover the affordability and accessibility dimensions of transportation at the same time. However, it is also important to enrich the picture with supporting indicators that help to improve the identification and analysis of the key factors that determine the prevalence of transport poverty.

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CRediT authorship contribution statement

E. Alonso-Epelde: Conceptualization, Methodology, Validation, Data curation, Writing – original draft, Writing – review & editing. **X. García-Muros:** Methodology, Validation, Writing – review & editing, Funding acquisition. **M. González-Eguino:** Validation, Writing – review & editing, Funding acquisition, Project administration, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Eva Alonso-Epelde reports financial support was provided by European Climate Foundation. Xaquin Garcia-Muros reports financial support was provided by European Climate Foundation. Mikel Gonzalez-Eguino reports financial support was provided by European Climate Foundation.

Data availability

Data will be made available on request.

Appendix A. Variables from the HBS

Table A1
Socioeconomic and demographic variables included

Variable	Values after transformation	Description
DECILE	D1-D10	Expenditure is used because it is considered a better proxy for permanent household income (Goodman and Oldfield, 2004). The equivalent spending deciles are calculated based on household spending relativized by the OECD's modified equivalence scale, thus taking into account the economies of scale generated in households based on their size. The modified OECD scale values the reference person in the household at 1, the rest of the members aged 14 or over at 0.5, and the rest of the members under 14 at 0.3.
QUINTILE	Q1-Q5	
AACC	Andalusia	Autonomous Community of residence
	Aragón	
	Asturias	
	Balearic Islands	
	Canary Islands	
	Cantabria	
	Castilla La Mancha	
	Castilla y León	
	Catalonia	
	Ceuta	
	Extremadura	
	Galicia	
	La Rioja	
	Madrid	
	Melilla	
	Murcia	
	Navarre	
	Basque Country	
	Valencia	
SIZEMU	Small municipality	Size of the municipality: A municipality is considered large when it has 10,000 inhabitants or more and small when it has fewer than 10,000.
	Large municipality	
DENSITY	Densely populated area	Population density of the household's place of residence
	Intermediate area	
	Sparsely populated area	
TYPEHH	Elderly alone	Type of household
	Single parent	
	Couples with children	
	Couples without children	
	Single person	
	Other	
OCUPATIONHH	All unemployed	Situation of the household with respect to occupation
	One employed	
	All employed	
	Not provided	
AGERP	Young	Age of the reference person: the reference person is considered young if he/she is 30 years old or younger, adult if he/she is between 31 and 64 years old, and elderly if he/she is 65 years old or older
	Adult	
	Elderly	
SEXRP	Female	Sex of the reference person
	Male	
COUNTRYRP	Spain	Country of birth of the reference person
	European Union	

(*continued on next page*)

Table A1 (*continued*)

Variable	Values after transformation	Description
	Rest of Europe	
	Rest of world	
STUDIESRP	No academic qualifications	Level of education of the reference person
	Primary education	
	Secondary education	
	Post-secondary education	
	Higher education	
WORKDAYPR	Full time	Type of working day of the reference person
	Part time	
	Not provided	
PROFSITRP	Self-employed	Occupational status of the reference person
	Employee	
	Employer	
	Other	
	Not provided	
TYPECONTRP	Indefinite	Type of employment contract of the reference person
	Fixed-term	
	Not provided	
TENUREREG	Rental	Tenure regime of the main home
	Assignment	
	Ownership with mortgage	
	Ownership w/o mortgage	

Source: Own work based on the information provided by the INE in the HBS

Table A2
Transportation expenses from the HBS

	COICOP[a]	Good/Service	Description
Private transport	07221	Diesel fuel	Diesel A, fuels for diesel engines, all kinds of mixtures. The 2 types of Diesel A are those permitted for cars in Spain: i) Regular Diesel A, normally known as Diesel A or Diesel and ii) New Diesel A, normally known as Diesel Premium or Diesel+.
	07222	Gasoline	All types of gasoline (gasoline 95, gasoline 98 …); all types of mixtures for all types of vehicles.
	07223	Other fuels for personal vehicles	Liquefied petroleum gas, alcohol, ethanol, methanol, butanol, biogas, biogasoline, hydrogen, biodiesel, electricity and mixture for two-stroke engines. Electricity cost of an electric car. In hybrid engines, the fuel part (if it is diesel or gasoline to codes 07.2.2.1 or 07.2.2.2 respectively) and the electricity part are broken down.
Transport Services	07311	Commuter train	Commuter train tickets and vouchers with a distance not exceeding 50 km. Annual commuter season tickets.
	07313	Subway and tram	Subway, tram or light rail tickets and vouchers when they are used only for these means of transport. This also includes annual metro, tram or light rail passes.
	07321	Non-school urban bus	Urban bus, minibus and trolleybus tickets. Bonobus passes used exclusively in this type of transport. Includes payments for baggage. Tourist bus.
	07322	Non-school intercity bus and coach	Collective intercity bus, minibus and trolleybus tickets. Bonobus passes used exclusively in this type of transport. Includes payments for baggage Long distance coach.
	07323	School transportation	All types of school transport, both urban and interurban, which the school or company makes available to students for travel
	07350	Combined passenger transport	Fares paid in advance for different means of transport in the city, such as Metrobus (combined metro and bus) Monthly and annual combined Metro and bus passes. Purchase of bonus recharge card. Combined tourist ticket Expenditure on the combined transportation of people and luggage in two or more modes of transportation, when the expense cannot be distributed between them. Private vehicle transportation.

Source: Own work based on the information provided by the INE in the HBS

[a] The Classification of Individual Consumption by Purpose (COICOP) is a classification developed by the United Nations Statistics Division to classify individual consumption expenditures incurred by households, non-profit institutions serving households and general government according to their purpose. The COICOP codes are essential to replicate the methodology since the HBS classifies household expenses according to the COICOP categories. In addition, this classification is used in other European statistics such as national accounts or the harmonized index of consumer prices.

Appendix B. Transport poverty metrics

Table B1
Transport poverty verification criteria and equations

Metric	Description	Equations for verification
10%	A household is classed as transport-vulnerable if it devotes more than 10% of its expenditure to meeting its mobility needs. Expenditure on transport is understood as spending on both private transport and short or medium-distance public transport services (see Table A2).	$\frac{T}{I} > 0.1$ Where T is equalized transport expenditure for each household and I is the household equalized income
2 M	A household is considered to be transport-vulnerable if the proportion of total expenditure devoted to transport is more than double the national median. In other words, these are households whose socioeconomic situation leads them to spend disproportionately to maintain a level of mobility appropriate to their needs. Expenditure on transportation is made up of the goods and services included in Table A2. The full sample is used to calculate the index, but to calculate the median expenditure we eliminate households that do not consume transportation goods or services, i.e. we calculate the median expenditure of households that spend money to meet their mobility needs.	$\frac{T}{I} > 2med_c\ (\frac{T}{I})$ Where T is equalized transport expenditure for each household, I is the household equalized income and med_c is the median calculated on households that expend on transport goods and services
LIHC	A household is considered as vulnerable to transport poverty if its disposable income after subtracting housing and transport costs is below the poverty threshold (which in Spain is set at 60% of the national median) (necessary condition i-nc.i) and if it spends more than the median on transportation (nc.ii). As in the 2 M index, expenditure on transportation is made up of the goods and services included in Table A2 and the median used is that which applies to households that consume transportation goods or services.	nc.i) $T \geq med_c(T)$ nc.ii) $(I - H - T) < 0.6med(I - H)$ Where T is equalized transport expenditure for each household, I is the household equalized income, H is the equalized housing cost of each household and med refers to the national median taking into account the whole population.
VTU	A household is considered a VTU if: i) its expenditure on transport is more than double the national median (nc.i); ii) its income is below the median for all households (nc.ii); and iii) its expenditure on public transport services is less than the national median once households that do not report expenses in these categories are removed (nc.iii).	nc.i) $\frac{T}{I} > 2med_c\ (\frac{T}{I})$ nc.ii) $I < med(I - H)$ nc.iii) $P > med_c(P)$ Where T is equalized transport expenditure for each household, I is the household equalized income, H is the equalized housing cost of each household, P is the household equalized public transport expenditure, med refers to the national median taking into account the whole population and med_c is the median calculated on households that expend on transport goods and services

Appendix C. Logit model

To identify the driving factors that explain the likelihood of suffering from transport vulnerability, we estimate a logit model in accordance with some of the main socioeconomic characteristics of households. This analysis seeks to identify the most vulnerable households, considering as vulnerable those with the greatest likelihood of incurring transport poverty. We consider households in transport poverty according to the LIHC and the VTU metrics and, following Legendre and Ricci (2015), which follows a similar approach for energy poverty, we estimate a logit model in which the dependent variable is one (Y = 1) if the household is in a situation of transport poverty and zero otherwise.[6] The logit model can be summarized as follows:

$$logit\ (P(Y=1|\ x_1,\ldots,x_n) = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n \quad \text{[E.1]}$$

where Y denotes whether the household is transport vulnerable according to the metric used. β_0 is a constant, and $\beta_{1\ldots n}$ is the slope coefficient associated with the explanatory variables $x_1,\ldots,x_n$. The explanatory variables introduced are i) Total household spending; ii) Size of the municipality of residence of the household; iii) Density of the municipality of residence of the household; iv) Gender of the household reference person; v) Level of education of the household reference person; vi) Age of the household reference person; vii) Country of birth of the household reference person; viii) Occupational status of the household reference person; and ix) Situation of the household with respect to occupation.[7] Table C1 shows all the explanatory variables introduced along with the categories included in each of them and the base category used.

Through the estimated coefficients from the logit model we can also estimate the probability ratios, which are calculated by taking the exponential of the coefficients estimated (Cameron and Trivedi, 2005):

$$logit(P) = \log\ (odds) = e^{\beta_1} = e^{\left[\log\left(odds_{x_1}/odds_{x_0}\right)\right]} \quad \text{[E.2]}$$

where $odds_{x_0}$ refers to the estimated coefficient for the reference category of a variable and $odds_{x_1}$ refers to the estimated coefficient for the category for which we are calculating the likelihood. Thus, the likelihood ratios calculated for both models enable us to analyze whether a type of household is more likely than the reference household to fall into a situation of transport vulnerability (likelihood ratio greater than 1) or vice versa (likelihood ratio less than 1).

[6] We use a logit model because it allows us to identify the probability that the household falls into transport poverty. These models have already been used with the same objective in energy poverty studies. The model is computed using R, which is a free and open language and environment for statistical computing and graphics.

[7] The selection of the independent variables for the logit model has been based on previous experiences in this type of analysis for energy poverty. In fact, we have taken into account variables that have already been analyzed in the literature (Legendre and Ricci, 2015; Romero et al., 2018).

Table C1
Independent variables included in the logit model

Independent variables	Categories
Total household spending	Equivalized total expenditure
Size of the municipality of residence of the household	Small municipality: Fewer than 10000 inhabitants
	Large municipality: 10000 inhabitants or more (base)
Density of the municipality of residence of the household	Densely populated area (base)
	Intermediate area
	Sparselypopulated area
Gender of the household reference person	Women (base)
	Man
Education level of the household reference person	No qualifications (base)
	Primary education
	Secondary education
	Post-secondary education
	Higher education
Age of the household reference person	Young (base)
	Adult
	Elderly
Country of birth of the household reference person	Spain (base)
	European Union
	Rest of Europe
	Rest of world
Occupational status of the household reference person	Other (base)
	Self-employed
	Employee
	Employer
Situation of the household with respect to occupation	Not provided (base)
	All unemployed
	One employed
	All employed

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Glossary

EC: European Commission
EU: European Union
ETS2: New Emission Trading System
SCF: Social Climate Fund
HBS: Household Budget Survey
INE: Instituto Nacional de Estadistica (Spanish Statistics Office)
2M: Disproportionate spending index
LIHC: Low Income High Cost
VTU: Vulnerable Transport User
CPI: Consumer Price Index