IEEE ITS Italian Chapter Annual Meeting

Best PhD Dissertation Award

June 5th 2023, Rome, Italy

Behavioral Models for Impact Assessment of Autonomous Driving on Travel Demand

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Background Concepts

"Autonomous Vehicles (AVs) are means of transport that are capable of *sensing* the environment and *moving* safely without human intervention"

Potential impacts on urban sub-systems

Transportation
- Infrastructure capacity (e.g. highways, parking spaces)
- Mobility choices (e.g. ownership or consumption?)
- Travel behaviors (e.g. individual or collective use?)

Land Use
- Accessibility
- Residential and Business location choices
- Urban form (e.g. urban sprawl)

Environment
- Local emissions (i.e. pollutants)
- Global emissions (i.e. greenhouse gases)
- Energy consumption

Economy
- Employment
- Real estate price

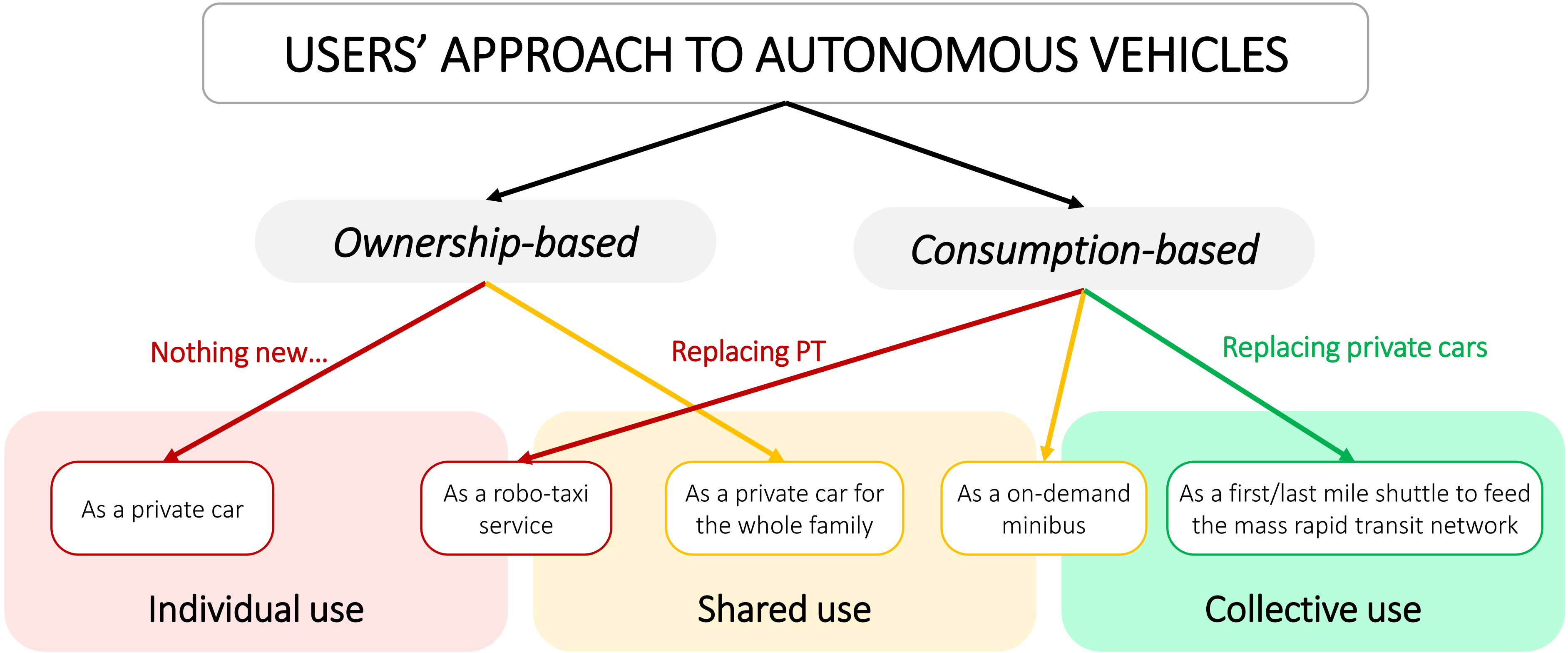
Society
- Quality of life
- Equity
- Road safety and cybersecurity

References:

- Milakis D., van Arem B., van Wee B., 2017. Policy and society related implications of automated driving. Journal of Intelligent Transportation Systems, 2017, Vol. 21, No. 4, 324-348.
- Duarte F., Ratti C., 2018. The Impact of Autonomous Vehicles on Cities: A Review. J. Urban Technol. 25, 3–18.
- Coppola P., Silvestri F., 2019. Autonomous vehicles and future mobility solutions. In Autonomous Vehicles and Future Mobility, AET series, Elsevier, ISBN: 978-0-12-817696-2.
- Silvestri F., De Fabiis F., Coppola P., 2022. Veicoli a guida autonoma e mobilità post-car. In Urban@It, Ottavo Rapporto sulle città, ISBN: 978-88-15-38276-4.

INTRODUCTION

Background Concepts



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INTRODUCTION

Demand-related Uncertainty Factors

User Acceptance

- *perceived usefulness*
- *perceived ease-of-use*
- *perceived safety and reliability*

Willingness-to-Adopt

- *willingness to pay*
- *willingness to hand over control to an artificial intelligence*
- *willingness to give up the pleasure of driving*

Behavioral Intention-to-

Own — Users **buy** AVs for **individual** use

Share — Users **share** AVs for **individual** use

Ride — Users **share** AVs for **collective** use

References:

- Davis F.D., 1989. Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. MIS Q. 13, 319–340.
- Ajzen I., 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process., Theories of Cognitive Self-Regulation 50, 179–211.
- Payre W., Cestac J., Delhomme P., 2014. Intention to use a fully automated car: Attitudes and a priori acceptability. Transp. Res. Part F Traffic Psychol. Behav., 27, 252–263.
- Nastjuk I., Herrenkind B., Marrone M., Brendel A.B., Kolbe L.M., 2020. What drives the acceptance of autonomous driving? Technol. Forecast. Soc. Change 161, 120319.

LITERATURE REVIEW

Autonomous Driving & Travel Demand Modeling

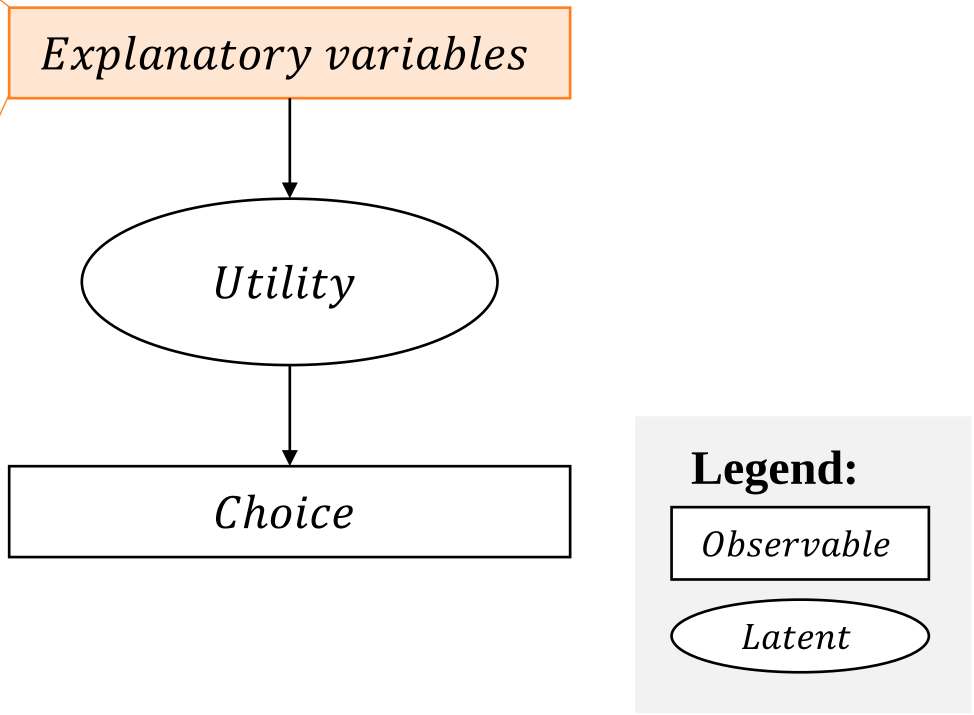
Observable factors

- **Level-of-Service attributes**
- **Socio-economic characteristics**
- **Travel habits**

References:

- Krueger R., Rashidi T.H., Rose J.M., 2016. Preferences for shared autonomous vehicles. Transportation Research Part C, 69, 343–355.
- Winter K., Cats O., Martens K., van Arem B., 2020. Identifying user classes for shared and automated mobility services. European Transport Research Review 12, 36.
- Asgari H., Jin X., Corkery T., 2018. A Stated Preference Survey Approach to Understanding Mobility Choices in Light of Shared Mobility Services and Automated Vehicle Technologies in the U.S. Transportation Research Record 2672, 12–22.
- Stoiber T., Schubert I., Hoerler R., Burger P., 2019. Will consumers prefer shared and pooled-use autonomous vehicles? Transportation Research Part D, 71, 265–282.
- Lavieri P.S., Bhat C.R., 2019. Modeling individuals' willingness to share trips with strangers in an autonomous vehicle future. Transportation Research Part A, 124, 242–261.

«Traditional» Behavioral Choice Model



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Autonomous Driving & Travel Demand Modeling

Observable factors

Level-of-Service attributes

Socio-economic characteristics

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Latent factors

Expectations

Concerns

Personal attitudes

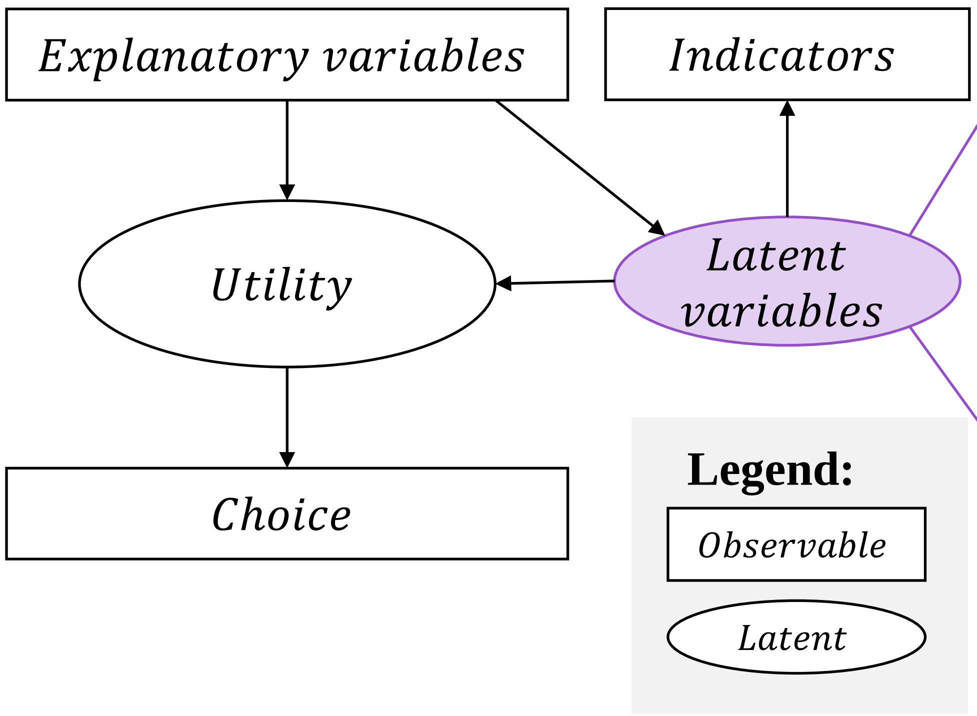
References:

- Haboucha C.J., Ishaq R., Shiftan Y., 2017. User preferences regarding autonomous vehicles. Transportation Research Part C, 78, 37–49.
- Chee P.N.E., Susilo Y.O., Wong Y.D., 2020. Determinants of intention-to-use first-/last-mile automated bus service. Transportation Research Part A, 139, 350–375.
- Acheampong R.A., Cugurullo F., 2019. Capturing the behavioural determinants behind the adoption of autonomous vehicles. Transportation Research Part F, 62, 349–375.
- Wang S., Jiang Z., Noland R.B., Mondschein A.S., 2020. Attitudes towards privately-owned and shared autonomous vehicles. Transportation Research Part F, 72, 297–306.
- Panagiotopoulos I., Dimitrakopoulos G., 2018. An empirical investigation on consumers' intentions towards autonomous driving. Transportation Research Part C, 95, 773–784.

LITERATURE REVIEW

Autonomous Driving & Travel Demand Modeling

«Hybrid»
Behavioral Choice Model



Latent factors

- **Expectations**
- **Concerns**
- **Personal attitudes**

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- Haboucha C.J., Ishaq R., Shiftan Y., 2017. User preferences regarding autonomous vehicles. Transportation Research Part C, 78, 37–49.
- Chee P.N.E., Susilo Y.O., Wong Y.D., 2020. Determinants of intention-to-use first-/last-mile automated bus service. Transportation Research Part A, 139, 350–375.
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RESEARCH CONTRIBUTION

A cross-sectional research that aims at **explaining individuals' behavioral intentions** w.r.t. different **potential approaches to autonomous driving**, investigating both **observable and latent factors**, and **profiling travelers' segments**.

Research Questions

- ***RQ1:*** *What are individuals' perceptions, expectations, safety concerns, and intentions towards autonomous driving?*
- ***RQ2:*** *How will autonomous driving change people's travel behaviors?*
- ***RQ3:*** *Which factors most explain users' heterogeneity towards owning, sharing or riding autonomous vehicles?*

METHODOLOGICAL APPROACH

I — Data collection

- Design and administration of a **Revealed Preference** (RP) / **Stated Intention** (SI) survey

II — Latent variables identification

- Specification of measurement models for the identification of **latent variables**

III — Model estimation

- Estimation of behavioral **Hybrid Choice Models: Panel Ordered Logit models with Latent Variables**

I) DATA COLLECTION

Revealed Preference / Stated Intention (RP/SI) survey

Collection strategy

- Revealed Preference (RP) / Stated Intention (SI) survey
- Computer Assisted Web Interviewing (CAWI)
- Random sampling
- 30 survey days (in January-February 2021)

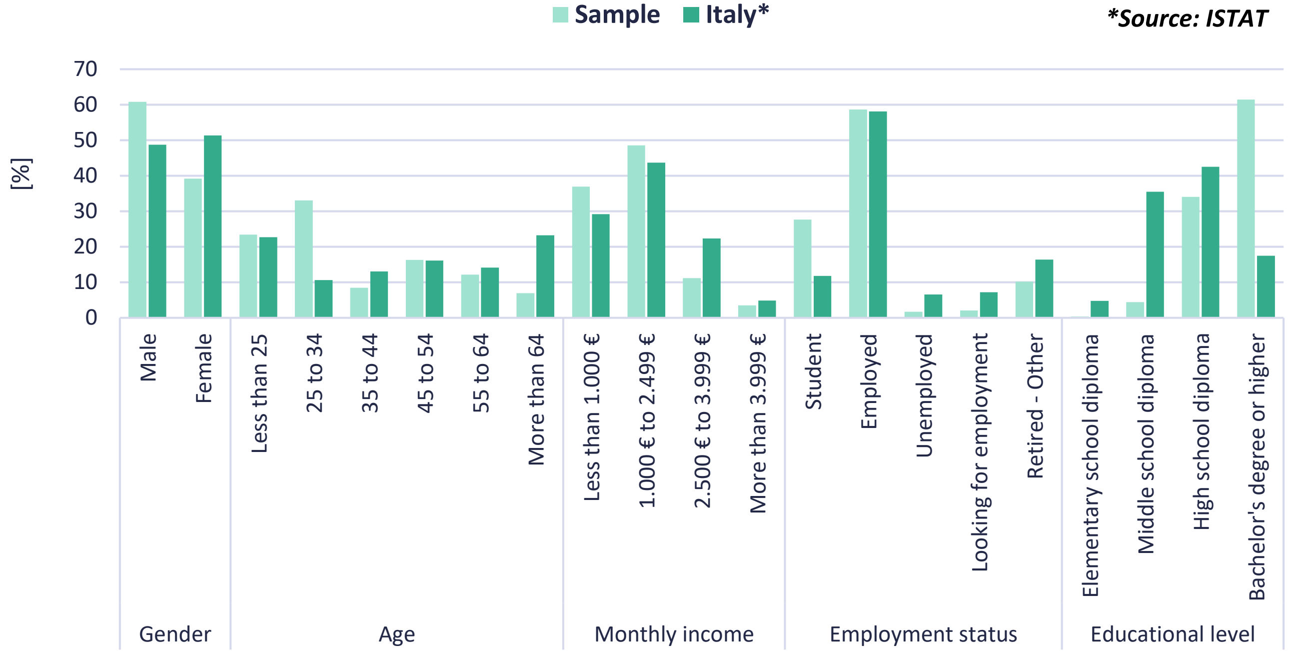
Sections of the questionnaire

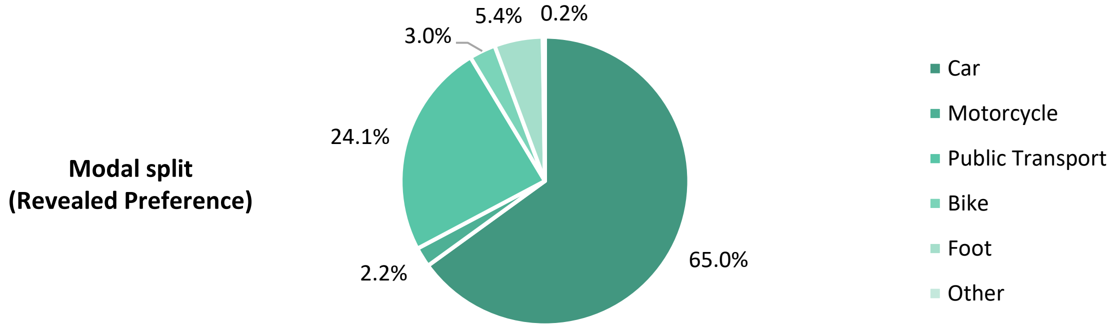
- Socio-economic characteristics
- Travel habits

Observable factors

- Perceptions about AVs
- Personal attitudes
- Intention-to-adopt AVs

Latent factors (Likert items indicators)





II) LATENT VARIABLES IDENTIFICATION

Measurement Models

Latent variables can be inferred from some observed data, called indicators, and differentiated through other observable explanatory variables (age, gender, travel frequency, travel purpose, etc.). The indicators could be for example responses to attitudinal questions, perceptual and motivational surveys.

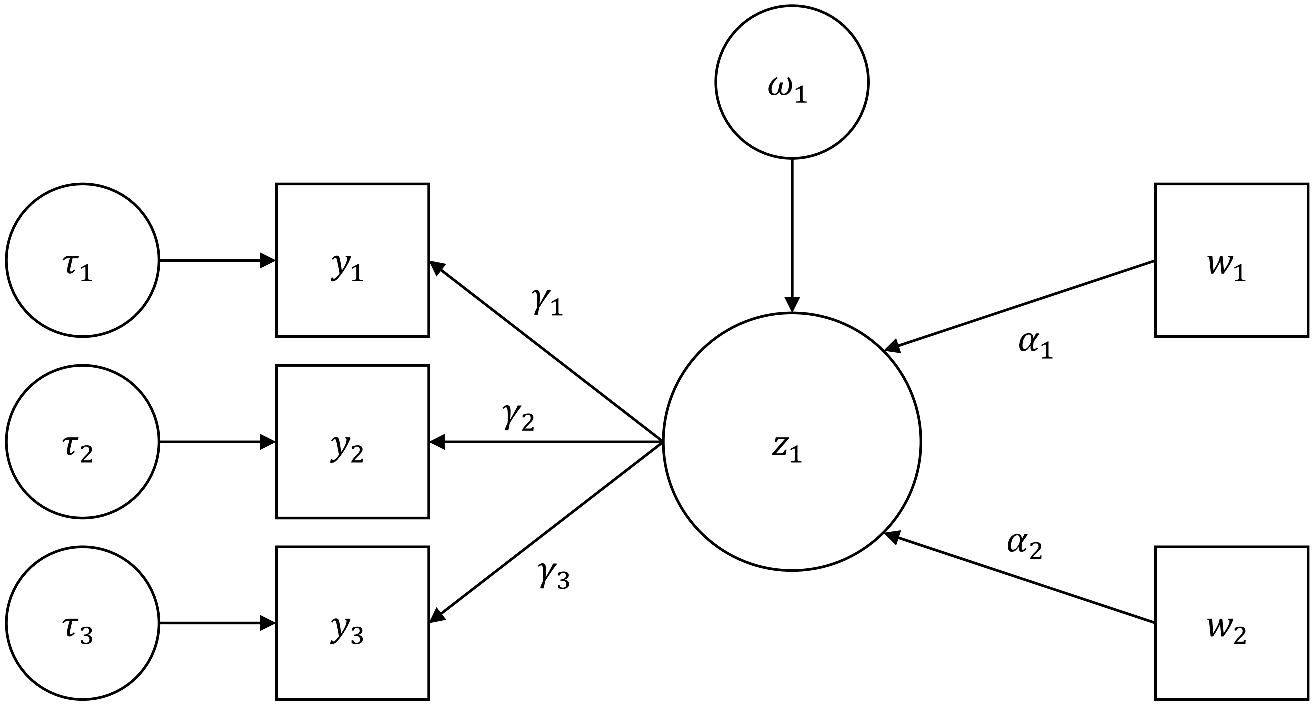
Latent variables are obtained through the specification of measurement models: essentially linear regression models where the main predictor, the factor, is latent or unobserved:

$$\boldsymbol{Y} = \boldsymbol{\gamma}\boldsymbol{Z} + \boldsymbol{\tau}$$

$$\boldsymbol{Z} = \boldsymbol{\alpha}'\boldsymbol{W} + \boldsymbol{\omega}$$

where $\boldsymbol{Y}$ is a set of endogenous observed indicators (items), $\boldsymbol{Z}$ are the latent variables of interest, $\boldsymbol{W}$ is a set of observable exogenous multiple causes of $\boldsymbol{Z}$, $\boldsymbol{\alpha}$ and $\boldsymbol{\gamma}$ are estimable parameters, and $\boldsymbol{\omega}$ and $\boldsymbol{\tau}$ are random errors.

e.g. MIMIC model in the case of one latent variable



Hybrid Choice Models: Ordered Logit

Therefore in the case of a ordered choice model the latent utility function y^* can be written as:

$$y^* = \boldsymbol{\beta X} + \boldsymbol{\delta Z} + \varepsilon$$

Latent behavioral intention-to-use AVs (y^*)

Observable factors ($\boldsymbol{\beta X}$)

Latent factors ($\boldsymbol{\delta Z}$)

where $\boldsymbol{X}$ are the attributes related to the transport solution and decision-maker, $\boldsymbol{Z}$ are the latent variables of interest, $\boldsymbol{\beta}$ and $\boldsymbol{\delta}$ are estimable parameters of the variables, and ε the random residual.

The continuous latent utility $\boldsymbol{y}^*$ is observed in discrete form through a censoring mechanism:

Observed counterpart of latent intention-to-use AVs (y)

$$\begin{aligned} y &= 1 \quad \text{if } -\infty < y^* < \mu_0 \\ &= 2 \quad \text{if } \mu_0 < y^* < \mu_1 \\ &= 3 \quad \text{if } \mu_1 < y^* < \mu_2 \\ &= 4 \quad \text{if } \mu_2 < y^* < \mu_3 \\ &= 5 \quad \text{if } \mu_3 < y^* < +\infty \end{aligned}$$

→

$$\begin{aligned} \text{Prob}(\boldsymbol{very\ unlikely}) &= \text{Prob}(y^* < \mu_0) \\ \text{Prob}(\boldsymbol{unlikely}) &= \text{Prob}(\mu_0 < y^* < \mu_1) \\ \text{Prob}(\boldsymbol{neutral}) &= \text{Prob}(\mu_1 < y^* < \mu_2) \\ \text{Prob}(\boldsymbol{likely}) &= \text{Prob}(\mu_2 < y^* < \mu_3) \\ \text{Prob}(\boldsymbol{very\ likely}) &= \text{Prob}(y^* > \mu_3) \end{aligned}$$

RESEARCH RESULTS

- ***RQ1:** What are individuals' perceptions, expectations, safety concerns, and intentions towards autonomous driving?*
  - **Intentions to adopt autonomous vehicles are not directly correlated with the socio-economic characteristics of individuals**
  - **Perceived Usefulness is positively correlated** with the willingness to adopt AVs, while **Cost concerns is negatively correlated**
  - Among the **personal attitudes** a slight correlation is observed between willingness to adopt AVs and **technology-savviness** (+ correlation), **propensity for sharing** (+) and **aversion to Public Transport** (-)
  - A strong positive correlation between the different willingnesses exists, testifying that **those who are most willing to use AVs, on average, are so for all three potential approaches** (own, share, ride)

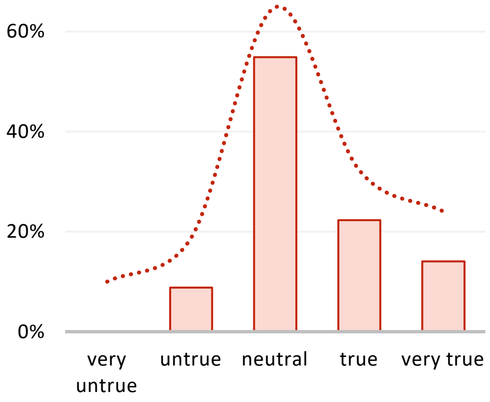
	Perceived Usefulness	Safety concerns	Cost concerns	Technology-savviness	Propensity for sharing	Aversion to Public Transport	Age group	Educational level	Income level	City extension	Willingness to experiment	Willingness to own	Willingness to share	Willingness to ride
Perceived Usefulness			***								***	***	***	***
Safety concerns				*								**		
Cost concerns	-0.17			*						*		***	***	***
Technology-savviness		-0.11	-0.10			*		***	**	**	***	***	***	***
Propensity for sharing						***	***		***	**			***	***
Aversion to Public Transport				-0.10	**-0.31**		**		**				**	***
Age group					**-0.38**	0.14			***		*	*	*	*
Educational level				0.19					***	***				
Income level				0.14	-0.28	0.16	**0.58**	0.26						
City extension				0.13	0.16			0.26					*	
Willingness to experiment	0.19			0.25								***	***	***
Willingness to own	0.19	-0.15	-0.22	0.23			-0.11				**0.44**		***	***
Willingness to share	**0.31**		**-0.31**	0.26	0.17	-0.16	-0.11			0.12	**0.37**	**0.46**		***
Willingness to ride	0.22		-0.28	0.20	0.22	**-0.30**	-0.12				**0.33**	**0.33**	**0.62**	

Spearman's rank correlation matrix. Statistical significance: *** p-value<0.001, ** p-value<0.01, * p-value<0.05

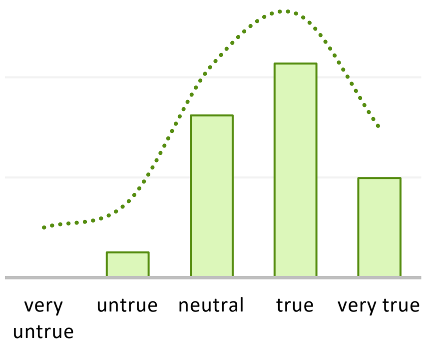
RESEARCH RESULTS

- ***RQ2:*** *How will autonomous driving change people's travel behaviors?*
  - **Users are more interested in sharing than owning AVs**
  - **Users are more interested in individual rather than collective use**

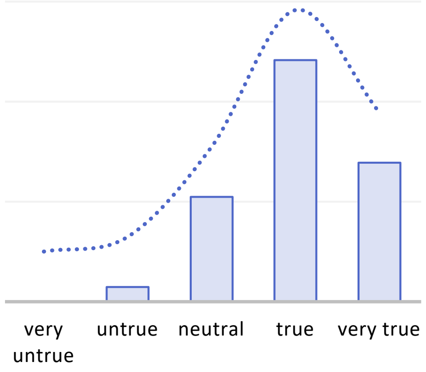
I will buy an autonomous car



I will use autonomous taxi services



I will use PT services with autonomous minibuses



MODEL 1	**Panel Ordered Logit Model with latent variables**
# observations	1218
Restricted log likelihood:	-16254.9
Final log likelihood:	-10287.6
Rho-squared	0.367
Akaike Information Criterion	20681.2

Observable Variable	**Coeff.**		**t-ratio**
Constant	5.71	*	1.71
Ownership (Yes = 1, No = 0)	-1.50	***	-7.83
Individual use (Yes = 1, No = 0)	0.63	**	2.04
Latent Construct	**Coeff.**		**t-ratio**
Perceived Usefulness	1.31	***	4.02
Safety concerns	-9.07	*	-1.69
Cost concerns	-5.27	**	-2.19
Technology-savviness	0.70	***	3.74
Propensity for sharing	0.60	**	2.40
Aversion to Public Transport	-1.20	***	-4.59
Thresholds Parameter	**Coeff.**		**t-ratio**
Mu(01)	1.42	***	12.20
Mu(02)	4.26	***	20.40
Mu(03)	6.99	***	17.80

***, **, * Significance at 1%, 5%, 10% level.

RESEARCH RESULTS

MODEL 2	Panel Ordered Logit Model with latent variables
# observations	1218
Restricted log likelihood:	-16254.9
Final log likelihood:	-10162.9
Rho-squared	0.375
Akaike Information Criterion	20447.9

- ***RQ3:*** *Which factors most explain users' heterogeneity towards owning, sharing or riding autonomous vehicles?*
    - **Safety concerns is the latent variable that impacts the most**, followed by the cost concerns
    - **Personal attitudes allow the profiling of the different demand segments**
    - Some **observable factors become significant when they are used to explain the heterogeneity in means** of some latent traits

Observable Variable	**Coeff.**		**t-ratio**
Constant	3.60		1.48
Ownership (Yes = 1, No = 0)	-1.74	***	-8.09
Individual use (Yes = 1, No = 0)	0.92	***	2.69
Gender (Female = 1, Male = 0)			
Age (More than 45 y.o. = 1, otherwise = 0)	-0.70	*	-1.81
Education (PhD or Master's degree = 1, otherwise = 0)			
Income (More than 2.500 € = 1, otherwise = 0)			
Household type (Live alone = 1, otherwise = 0)	-1.22	***	-3.69
City extension (More than 100.000 inhabitants = 1, oth. = 0)			
Travel frequency (More than 4 times per week = 1, oth. = 0)			
Latent Construct	**Coeff.**		**t-ratio**
Perceived Usefulness	0.46	**	2.08
Safety concerns	-7.42	**	-2.21
Cost concerns	-5.96		-1.64
Technology-savviness	2.57	***	3.43
Propensity for sharing	1.10	***	3.40
Aversion to Public Transport	-1.37	***	-4.77
Heterogeneity in Mean	**Coeff.**		**t-ratio**
Perceived Usefulness | Household type	-0.13		-1.50
Safety concerns | Gender	-1.40	**	-1.97
Cost concerns | Income	-0.10		-0.65
Technology-savviness | Age	-0.54	***	-5.43
Propensity for sharing | City extension	0.45	***	4.44
Aversion to Public Transport | Preferred mode: Car	-0.67	***	-5.33
Thresholds Parameter	**Coeff.**		**t-ratio**
Mu(01)	0.88	***	16.40
Mu(02)	2.38	***	12.30
Mu(03)	5.36	***	20.70

***, **, * Significance at 1%, 5%, 10% level.

CONCLUSIONS & RESEARCH PERSPECTIVES

- The **SP/SI survey** designed with the **Likert method** allows to effectively measure the personal **attitudes** of individuals and their **expectations** on (any possible) emerging technology

- The behavioral models with **latent variables** allow to highlight the possible **existence of heterogeneity among individuals**

- ❑ **Including latent traits** of individuals **in discrete choice models** leads to the estimation of **more robust models**

- ❑ **Observable factors** (such as socio-economic characteristics and travel habits) **can be explanatory exogenous variables of the heterogeneity in means** of the latent variables

- ❑ When dealing with **uncertainty**, as in the case of a disruptive technology such as autonomous driving, the **latent factors explain most of the travelers' intention-to-adopt a new transport solution**

CONCLUSIONS & RESEARCH PERSPECTIVES

- **The consumption-based** (as a service) **approach to autonomous driving rather than ownership-based** (as a product) **is predominant, but also an individual rather than collective use of AVs**

- **Automation could be the driving force for a sustainable development of future mobility**, which will allow to overcome the current car-ownership model even if not the car-oriented model of urban mobility

- **Age has been found to be a determinant of the intention to adopt AVs:** this result bodes well given that the new generations will be the potential users of these transport solutions.
- **Gender gaps in expectations about autonomous driving exist**: females on average have a stronger sense of safety concern
- **The costs for taking advantage of this new technology are an important issue**

- **Transport policies will need to be inclusive**, and take into account the needs of vulnerable demand segments such as the elderly and females
- **Travel Demand Management measures that encourage collective transport will foster social equity**, meeting the needs of those with less economic resources
- Research now have to focus on the design and simulation of such policies for the **evaluation of the wider impacts of autonomous driving on environment, society and land use**

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Thank you for your attention!

Fulvio Silvestri
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