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Exploring the impact of autonomous vehicles on youth mobility through focus groups and simulations

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ABSTRACT

The imminent introduction of autonomous vehicles (AVs) represents a significant revolution in transportation, offering unique opportunities to enhance the sustainability and efficiency of urban transport systems. This study uniquely combines qualitative focus groups with European school students and quantitative activity-based simulation models to compare teenagers' reactions to AVs. Focus groups gathered insights into their current mobility habits and perceptions of AVs. The simulation model then evaluated the potential impacts of AVs, specifically robotaxis and autonomous shuttles, on teenagers' travel behaviour in Santander, Spain. The results reveal a strong interest in AVs among teenagers, particularly for the independence and flexibility they offer. However, practical considerations such as cost, availability, and parental preferences continue to influence their mobility choices. The simulation results indicate a significant shift towards robotaxis, reducing walking and public transport usage. Gender-specific preferences were also noted, with girls being more likely to use robotaxis. The findings underscore the need for policies that balance AV usage with active modes and public transport, address safety concerns, and ensure equitable access to AVs. The study highlights the benefits and challenges of integrating AVs into teenagers' lives, offering insights for policymakers and technologists. Further research is needed to validate these findings through real-world trials and to explore the long-term impacts of AVs on teenagers' mobility, physical activity, and social interactions.

1. Introduction

The impending launch of autonomous vehicles (AVs), driven by substantial investments (Orieno et al., 2024; "The autonomous vehicle industry moving forward | McKinsey," n.d.) and technological advancements (Biswas and Wang, 2023), represents a significant revolution in transportation. This transition presents a unique opportunity to enhance the sustainability of urban transport systems. However, careful planning and understanding are essential to mitigate potential negative externalities and maximise the benefits of AVs. Negative externalities such as increased traffic congestion and urban sprawl could be worsened by the convenience and accessibility of AVs, leading to potential rebound effects (Garus et al., 2023). Conversely, the successful integration of AVs could contribute to improved air quality by reducing the number of vehicles, as well as reducing traffic fatalities through safety features and adherence to traffic laws. Enhanced urban mobility could be realised by offering flexible, efficient and convenient transport options, reducing the reliance on personal car ownership. This could be most likely achieved by the regulated implementation of AVs that best serves the city and its inhabitants as a whole through shared services and optimised public transport systems (Alonso Raposo et al., 2019).

Understanding how different demographic groups will react to AVs is crucial for their successful integration. Teenagers, in particular, represent a demographic whose travel behaviours and modal choices could be significantly impacted by the availability of AVs (Garus et al., 2022; Mourtzouchou et al., 2022). Mobility during adolescence plays an important role in shaping not only independence, but also access to education, social activities, and long-term transport habits. Up to now, transportation systems have overlooked teenagers' needs, often limiting their autonomy and reinforcing dependence on parents or guardians.

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AVs could disrupt this dynamic, offering new possibilities for independent travel, while also raising concerns about safety, physical activity, and social interaction. Today, teenagers face limited modal choices, often constrained by the need for a driving license. The introduction of AVs, which do not require a license, could offer them new mobility options and alter their travel behaviour. This shift could have dual implications: on one hand, it might reduce physical activity if teenagers opt for AVs overactive travel such as walking or cycling to school; on the other hand, it could alleviate traffic congestion around schools by reducing the number of parents driving their children. Moreover, AVs could provide a social space for teenagers, fostering interactions during commutes. Therefore, it is essential to understand these behavioural changes to ensure that AVs contribute positively to sustainability, quality of life, and the safety of teenage users.

To gain comprehensive insights, this mixed-method study combines qualitative data from focus groups with quantitative activity-based simulation modelling. This approach allows a comparison between teenagers' expressed preferences and simulated travel behaviours related to autonomous vehicles. This understanding would inform the design of sustainable transport systems, specifically evaluating the potential of autonomous shuttles and robotaxis.

The main contributions of this study are summarised as follows:

- **Mixed-method approach:** By integrating qualitative focus groups with quantitative activity-based simulations, the study offers a unique, comprehensive understanding of teenagers' mobility by comparing their stated preferences with simulated travel behaviours.
- **Focus on teenagers as a crucial demographic segment:** Addressing a demographic often overlooked in AV research, whose travel choices are currently limited due to licensing, highlighting potential behavioural changes brought by AV adoption.
- **Evaluation of AV impacts on sustainability and mobility:** Examining how AV services such as robotaxis and shuttles may influence mode choice, physical activity, and traffic patterns, assessing both benefits and risks.
- **Policy-relevant insights:** Offering actionable recommendations for AV integration in urban transport systems, with a focus on shared AV services, safety considerations, and equitable access tailored for teenagers.

Grounded in these contributions, the study seeks to address key questions that link teenagers' mobility behaviours with the broader implications of AV deployment. Specifically, the research investigates the following:

1. How did the simulated choices of teenagers regarding AV use compare with their expressed preferences in focus groups?
2. What are the potential impacts of autonomous shuttles and robotaxis on teenagers' travel behaviour, sustainability, and quality of life?
3. How can AVs be integrated into urban transport systems to maximise benefits and minimise negative externalities for teenage users?

The paper first reviews the literature on teenagers' mobility, including challenges, the limited AV research focused on them, and parents' perspectives. It then covers AV services, examining simulation studies on service frequency, vehicle occupancy, and operational costs. This is followed by a description of the mixed-methods research approach, which includes focus groups and activity-based simulations conducted in Santander, Spain. Next is a presentation of results concerning teenagers' attitudes toward AVs and the effects of robotaxi and shuttle scenarios on travel behaviour. The discussion explores the benefits, risks, and policy implications of these findings, with an emphasis on safety, trust, and equitable access. The paper concludes by summarising its contributions, acknowledging limitations, and suggesting future research directions.

2. Literature review

Research shows that teenagers have distinct views and attitudes towards AVs, influenced by their unique mobility challenges, which are comparable to those faced by the elderly and individuals with impairments (Harper et al., 2016; NHTSA, 2017). Wu et al. (2021) listed teenagers among eight transport-disadvantaged groups who exhibit heightened sensitivity to AV impacts due to restricted driving privileges and geographic isolation. With driver's licenses typically unavailable until age 16 and parental safety concerns further limiting mobility, teenagers face significant transportation barriers that AVs could potentially address (Harper et al., 2016; Sparrow and Howard, 2017).

Despite their specific mobility needs, teenagers remain understudied in AV research. Existing studies predominantly focus on parents' opinions rather than directly capturing teenagers' perspectives, largely due to the difficulty in reaching minors and requiring parental consent. Recent usability research has partially addressed this gap by directly involving children aged 7–14 in testing AV prototypes, revealing that they can successfully transfer their existing knowledge from cars and technology to operate AV features independently (Stange et al., 2025). However, only two studies have directly explored teenagers' perspectives (Ngwu et al., 2022; Mourtzouchou et al., 2022) with findings showing that teenagers recognise AV benefits but express safety concerns that make them reluctant early adopters. In addition, a study on a shared autonomous vehicle (SAV) demonstration at a university campus examined how younger students, typically early adopters of technology, would accept SAVs. Using survey data, it analysed factors influencing their inclination to adopt SAVs, providing insights into younger demographics' experiences with AVs (Etminani-Ghasrodashti et al., 2025).

The line of research on parents' opinions about AVs for child transportation is extensive. Lee and Mirman (Lee and Mirman, 2018) identified two parent groups: "curious" enthusiasts and "practical" cautious users who see AV potential despite challenges. More recent research examining German parents' willingness to use AVs for unaccompanied child transportation found that the majority of parents were willing to use AVs for their children, but only after gaining initial experience with the vehicle and training their children in its use (Stange et al., 2024). Notably, parents based their consent on their children's emotional and cognitive abilities rather than chronological age, and intended to replace most accompanied leisure car journeys with AV transportation while preserving active mobility options like walking and cycling.

Tremoulet et al. (2020) found that children were uncomfortable riding AVs alone, and only 21 % of parents approved, citing reasons linked to the maturity readiness of each child, weather conditions, and maintenance. Anania et al. (2018) reported that parents were less willing to let their children use driverless school buses, with this decision influenced by factors such as gender, nationality, and emotions. The study of Jing et al. showed that parents' willingness to use AVs for school commute was found to be influenced by the perceived usefulness and greater understanding of AVs (Jing et al., 2021). This intention decreased when there was a higher perception of risk. Koppel et al. (2021) revealed parents generally hesitated without reassurance features like cameras and emergency contact options, with views varying by children's age, parents' age, location, and safety concerns.

Focus group discussions, a qualitative research method, entail guided conversations among small participant groups. These discussions effectively explore public concerns on emerging scientific advancements and promote participatory governance (Macnaghten, 2021). Focus groups are also commonly used in technology studies, including mobility and transportation research (Duboz et al., 2022; Karlsson et al., 2020; Lee et al., 2021; Montoya-Robledo et al., 2020; Ngwu et al., 2022; Sipone et al., 2019), as they allow researchers to reveal detailed insights into users' perceptions, experiences, and attitudes, through interactive discussions, enabling dynamic group interactions (Guest et al., 2017; O. Nyumba et al., 2018).

Nevertheless, the findings from focus groups are often not generalizable due to the non-random and pre-selected nature of the sample (Cyr, 2019). Therefore, simulation studies are often used to anticipate the effect of new mobility services. In particular, activity-based models (ABMs) are utilised to predict the impacts of AVs on travel behaviour and transportation systems (Silva et al., 2022). Due to ABMs' ability to incorporate individual-level data which allows detailed analysis of behavioural shifts (Garus et al., 2022).

Various AV services have been modelled, including shared autonomous vehicles (SAVs), also known as robotaxis and autonomous shuttles, also referred to as autonomous public transport on demand (Li et al., 2021). For example, agent-based simulations have been used to assess autonomous shuttles in Zurich, considering factors like service frequency, vehicle occupancy, and operational costs (Räth et al., 2023). Studies focusing on robotaxis have examined their potential to reduce private car ownership and improve urban mobility, showing significant impacts on traffic patterns and parking demand, but also warning of potential negative externalities such as increased vehicle kilometres travelled (VKT) and urban sprawl (Garus et al., 2024; Li et al., 2021; Maheshwari and Axhausen, 2021). Studies have evaluated how AVs affect energy use and GHG emissions, considering both direct effects and operational efficiencies (Garus et al., 2022; Gawron et al., 2019; Kopelias et al., 2020; Silva et al., 2022; Sun et al., 2022). ABMs have also assessed changes in travel behaviour, such as shifts from private cars to SAVs, and improvements in traffic flow (Berrada and Leurent, 2017; Garus et al., 2023; Golbabaei et al., 2021; Othman, 2022). Service performance metrics such as waiting times, coverage, and cost-effectiveness indicate potential reductions in vehicle fleets and parking demand (Li et al., 2021; Maheshwari and Axhausen, 2021; Othman, 2022; Räth et al., 2023). However, despite the extensive use of ABMs, there is a notable scarcity of results of simulation studies focusing specifically on teenagers, highlighting a gap in understanding this demographic's unique travel patterns and preferences.

This study fills both gaps by combining focus groups and simulation modelling to explore teenage attitudes toward AVs. This mixed-method approach merges qualitative insights with quantitative predictions, offering a comprehensive view of teenagers' potential AV adoption; an under-explored group with significant mobility needs.

3. Methodology

This mixed-method study combined qualitative and quantitative methods by comparing findings from focus groups conducted across Europe with simulation results from Santander, Spain. The methodology was structured in two parts: first, qualitative data collection and analysis through focus groups to capture teenagers' perceptions and preferences regarding AVs; second, an activity-based simulation model to evaluate the potential impacts of AVs on teenagers' travel behaviour in Santander under different scenarios, including the current state, the introduction of robotaxis, and the implementation of autonomous shuttles. The results of the focus group discussions were used to develop scenarios, which were analysed in the simulation study.

3.1. Focus groups

The recruitment process targeted teenagers from all 13 European Schools,[1] which spanned Belgium, Germany, Italy, Luxembourg, the Netherlands, and Spain. An open call was issued and disseminated to all students via email and posted in the announcement areas of their respective schools. Participation was voluntary and required parental consent, along with a basic understanding of the English language for discussion purposes. The study was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Board of the European Commission's Joint Research Centre (30425_1_03062021, 3 June 2021).

Data collection involved both physical and online settings. Five focus groups were organised between September and December 2021: three in-person with 15 participants and two online with 16 participants, totalling 31 teenagers (18 girls and 13 boys) with an average age of 15.9 years (ranging from 14 to 17 years). In-person participants were from the European School of Varese, Italy.

Each focus group lasted two hours and included 5–8 participants. Discussions were facilitated by a moderator and a co-moderator, both members of the research team. For in-person focus groups, an external recording device was used, while the online sessions were recorded using the built-in functionality of Microsoft Teams. All recordings were anonymised before being transcribed verbatim. The discussions adhered to a predefined framework established by the research team.

The transcripts were then imported into the qualitative data analysis software MAXQDA for thorough categorisation and coding. We employed a combined inductive and deductive method to apply top-level codes to all transcripts. Our custom coding system was utilised for specific segments, and additional codes were identified inductively through the analysis process. To ensure consistency and reliability during the coding process, inter-coder reliability testing was applied. Two researchers-coders, separately and without being influenced by each other, analysed the agreed-upon coding system, and in a second step, they compared it to eliminate discrepancies.

3.2. Simulation study

Santander, Spain (population 172,957), was selected as the case study due to its optimal balance of transport dynamics complexity and manageable size for microsimulation. Detailed travel choice information was available from a 2013 transport diary survey (sample size 1,384), which included all trips made by individuals within households, along with socioeconomic data about the households and their members.

The simulation process followed four main steps (Fig. 1). First, we used a population synthesis tool to create a realistic virtual population of Santander, including details such as age, gender, household composition, and travel habits. This allowed us to model how different types of people move around the city. In the second step, we applied an activity-based demand model to generate daily travel schedules for each individual, including their destinations, timing, and choice of transport mode. Third, we introduced autonomous vehicles, both robotaxis and shuttles, into the model and used an optimisation engine to simulate how these services would be managed in real time, including ride-sharing, vehicle routing, and pick-up coordination. Finally, all trips were simulated in detail using Aimsun, a traffic simulation platform that captures how vehicles move through the city's road network. This step allowed us to analyse traffic and environmental impacts, travel times, and how AVs could interact with other transport modes. Together, this modelling chain allowed us to compare different scenarios and evaluate how AVs might affect teenagers' mobility in an urban environment.

The population synthesis was conducted using a variational autoencoder to create a detailed representation of individuals and households (Borysov et al., 2018). This included sociodemographic attributes such as age, gender, income, occupation, household size, main occupation location and household location. Vehicle ownership was modelled at the household level using a multinomial logit model (MNL).

The demand estimation was carried out using SimMobility, an open-source simulation platform developed by the Singapore-MIT Alliance (Adnan et al., 2016). This study specifically used the Pre-day module of SimMobility, an ABM that generates daily activity schedules for a synthetic population.

The Pre-day ABM primarily uses discrete choice models based on random utility theory, with most models being MNL and nested logit (NL) models, organised hierarchically into three levels: day-pattern, tour, and intermediate stop levels. This framework implies that an individual (n) assesses each of the available options based on the

[1] https://www.eursc.eu/en/European-Schools/mission

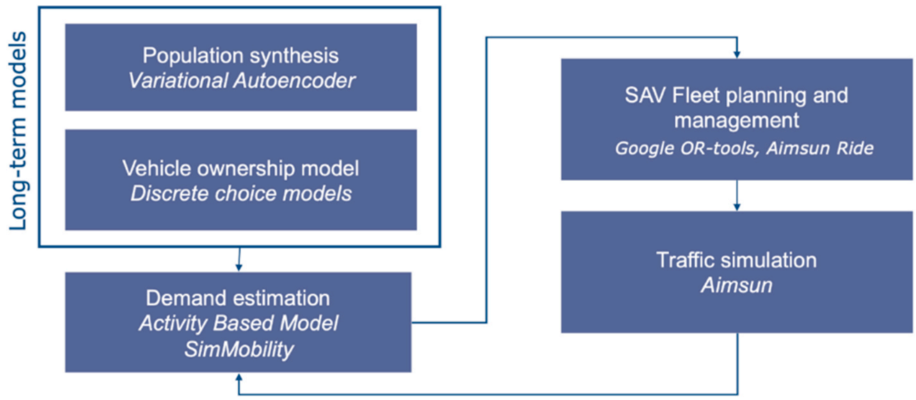

Fig. 1. Overview of the model components used in the study.

perceived utility of each alternative and makes the choice that maximises the utility. The utility (U) is composed of a deterministic part – a vector of the explanatory variables as well as the attributes of the alternative and the socioeconomic characteristics (Xn) of the individual – and a stochastic component – an error term (ε) that accounts for all variables unknown or omitted by the modeller. As an additive linearity is assumed, the utility of alternative i can be expressed as follows (Ortúzar and Willumsen, 2011):

$$U_{in} = \beta_i X_n + \varepsilon_{in} \tag{1}$$

Where β is the vector of coefficients to be estimated.

At the day-pattern level, MNL models predict the occurrence of tours and intermediate stops for various purposes, including work, education, shopping, leisure, and others. This level generates a list of tours and potential stops for each individual in the synthetic population. The tour level includes discrete choice models that predict the destination, mode, and timing (arrival and departure times) of each tour (Oh et al., 2020). Finally, at the intermediate stop level, models predict the destination, travel mode, and timing for secondary activities. The ABM simulation yields detailed activity schedules for the entire population, including timing, destination at the zonal level, and travel mode for each tour.

The utility function coefficients were derived from this travel diary data and estimated using Biogeme software (Bierlaire, 2020). The utility functions incorporated individual attributes and parameters specific to the model, such as age, gender, main activity type, occupation, household income, household size, vehicle ownership, VOT, cost, alternative-specific coefficients, and outputs of utility of lower-level models. More than 200 parameters were estimated to accurately represent the behaviour of Santander's population. The detailed scheme of the Pre-day SimMobility model is presented on Fig. 2 hereunder. The model was validated and calibrated using real-world data from the Santander Transport Diary Survey. Calibration involved adjusting the model parameters, specifically alternative specific constants, to ensure that the simulation outputs closely matched observed travel behaviour and traffic patterns.

The management of autonomous services was optimised using Google OR-Tools (Perron and Furnon, 2022). OR-Tools facilitated the routing and scheduling of SAVs, ensuring efficient service provision while minimising wait times and travel distances. Fleet management involved matching ride requests to vehicles, using the capacitated vehicle routing problem (an optimisation method for efficiently

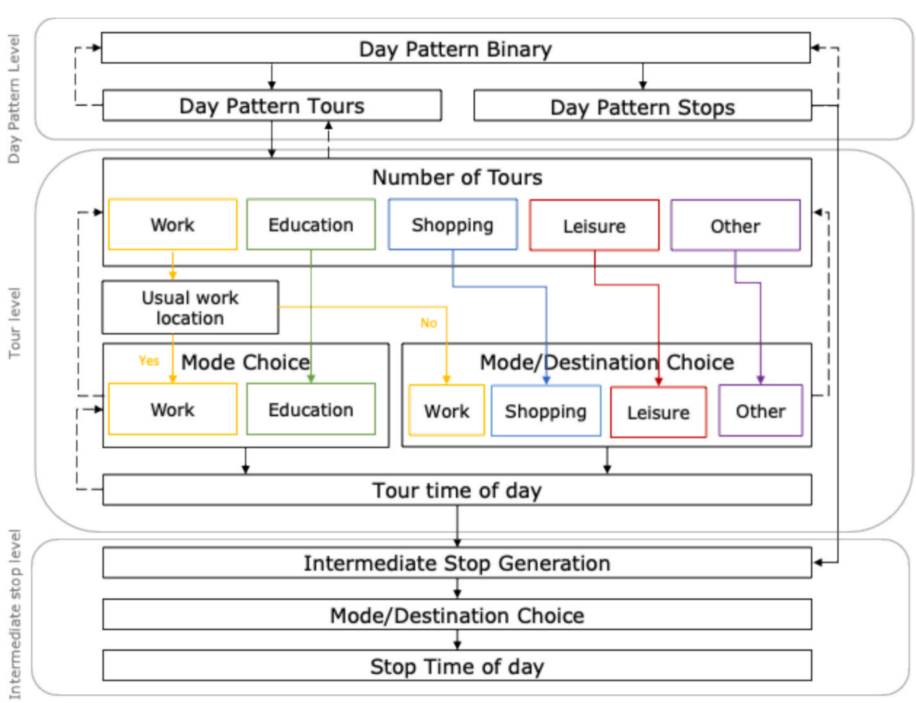

Fig. 2. Detailed description of SimMobility simulation platform.

matching passengers to vehicles) with time windows (CVRPTW). The fleet operator aimed to handle all ride requests while minimising the total fleet distance. Requests included pick-up and drop-off locations, time windows, and the number of passengers.

The supply-side simulation was conducted using Aimsun, which supports detailed microscopic, mesoscopic, and hybrid simulations (Aimsun, 2023). Aimsun enables the accurate modelling traffic flow and vehicle interactions within the urban transport network. More detailed information about the model development, data sources and key assumptions could be found in (Garus et al., 2025).

As previously mentioned, the Pre-day simulation generated activity schedules for each individual in the population. This data was processed using a Python script to create origin–destination matrices, which were then used as demand input for Aimsun Next. The traffic simulation in Aimsun employed a microscopic traffic simulation with static path assignment combined with dynamic path reassignment for 30 % of vehicles, updated every 5 min, with an 80 % compliance rate and enroute option activated. The simulation included car, SAV trips, and public transportation based on the current bus schedule. SAVs were modelled by adjusting car-following, lane-changing, and gap acceptance models according to the literature (Makridis et al., 2020; Nickkar and Lee, 2019; Talebpour and Mahmassani, 2016).

Three simulation scenarios were developed to evaluate the impact of AVs on teenagers' travel behaviour. These scenarios were based on the focus group discussions, where participants expressed a strong interest in both robotaxis and autonomous shuttles on demand as appealing options for AVs. Consequently, these two scenarios, along with the base case representing the current state of transportation, were analysed through an activity-based model. The assumptions for these scenarios were derived from a comprehensive literature review and validated with expert opinions from industry leaders in the CCAM organisation, specialising in automation. Apart from modal-specific assumptions, a 20 % reduction in vehicle ownership was presumed, particularly in households with more than two vehicles. Three different scenarios were created to see how AVs might change how teenagers travel:

- **Current State:** This scenario represents existing transportation conditions, with available modes including Car, Bus, Motorbike /Bike, and Walking. Some teenagers have driving licenses, but the majority do not. This scenario reflects the current modal choices and travel patterns observed in Santander.
- **Robotaxis:** In this scenario, AVs are introduced as robotaxis that can be easily ordered for both private and shared rides. This scenario includes travel options such as Car, Bus, Motorbike /Bike, Walking, and Robotaxi. The availability of robotaxis is associated with a lower VOT since passengers do not have to drive. Assumptions for this scenario are based on literature and expert opinions, suggesting a mix of shared and private rides with a maximum occupancy of 4 passengers per vehicle. The VOT is set at 70 % of that for a car as a driver for a private ride and 90 % for a shared ride. Maximum wait times are 10 min, with costs including a flat fee of €2.5 plus €2.4/km for private rides and €1.8/km for shared rides.
- **Autonomous Shuttles:** In this scenario, AVs are introduced as larger shuttle vehicles offering only shared rides. These shuttles aim to fully replace existing bus services and allow for on-demand pick-up and drop-off. The available transportation modes in this scenario include Car, Bus, Motorbike /Bike, Walking, and Shuttle. Assumptions for this scenario, validated by CCAM experts, include a maximum occupancy of 15 passengers per shuttle. The VOT is similar to current bus services, but with no access and egress time due to the on-demand nature. The maximum wait time for a shuttle is set at 15 min, with costs including a flat fee of €1 and an additional €0.5/km travelled.

4. Results and discussion

This section presents the results of the two studies, the focus group discussion and the simulation studies of the three analysed scenarios.

4.1. Focus group findings

Teenagers primarily relied on passive transport modes such as school buses, public transport, private cars driven by parents, and carpooling with friends. Active modes, such as biking and walking, were typically used under favourable weather conditions or when the school was in close proximity. Some participants mentioned combining multiple transport modes to reach their destinations, such as being driven to bus stops, walking to train stations, or using a mix of public transport modes (bus, train, tram). This multimodal approach resulted in complex mobility patterns, which was an important finding not widely discussed in existing literature.

Teenagers generally viewed AVs positively, associating them with lower emissions, increased reliability and safety, independence from needing a driving license, and improved comfort. They described AVs as "revolutionary and futuristic technology". However, ethical concerns were raised about decision-making in accidents and the need for human intervention in certain situations. Participants were divided on the necessity of human oversight, with some advocating for human control to handle technology failures and ethical decisions, while others trusted the superior precision of machines over human drivers. Regarding their potential use of AVs, most teenagers indicated a willingness to use them, particularly for daily commuting, if they achieved comparable or lower error rates than human drivers. Some preferred AVs for long-distance travel in a fully automated and connected transport system. Those who were conditionally willing to use AVs emphasised the importance of trust-building through safety tests and compliance with high safety standards. A minority expressed a preference for traditional driving, citing the enjoyment and sense of independence it provides. Safety concerns, including potential terrorist attacks or hacking, and infrastructure adequacy, were also mentioned by those undecided about AV use.

Teenagers identified several advantages and disadvantages of AVs. Societal advantages included improved traffic management, reduced accidents, and increased accessibility for various groups, such as senior citizens, people with disabilities, minors, and those without a driving license. Individual benefits included the ability to engage in other activities while travelling and enhanced comfort and safety compared to conventional vehicles. Disadvantages at the societal level included high initial costs, increased energy consumption for production and operation, and potential job losses in driving professions. Environmental concerns were noted, particularly the risk of overuse leading to reduced physical activity, such as walking and cycling. Individual-level disadvantages included safety concerns about control loss and software bugs, trust issues with AI decision-making, and potential loss of driving skills. The advantages and disadvantages identified by teenagers are presented in Table 1, which organises their perspectives at both societal and individual levels.

Further analysis of the focus group data reveals nuanced perspectives on mobility and AVs. Teenagers expressed frustration with the current transport infrastructure, citing unreliable public transport schedules and poor road conditions as significant issues. The dependence on parents for rides due to inadequate public transport options was a common theme, highlighting a desire for more independence in mobility choices.

The perception of AVs as a means to gain independence was strong among participants. They saw AVs as a potential solution to their mobility challenges, particularly for those without a driving license. The promise of reduced travel times and the ability to use travel time productively were significant advantages. However, concerns about safety, trust in technology, and the potential loss of driving skills persisted.

Teenagers also highlighted the social implications of AVs. They

Table 1
Perceived advantages and disadvantages of autonomous vehicles.

Level	Advantages	Disadvantages
Societal	• Improved traffic management • Reduced accidents • Increased accessibility for seniors, disabled, minors • Lower emissions	• High initial costs • Increased energy consumption • Job losses in driving professions • Reduced walking and cycling
Individual	• Engage in activities while traveling • Enhanced comfort and safety • Independence from driving license • Increased reliability	• Safety concerns about control loss • Software bugs and technical failures • Trust issues with AI decision-making • Potential loss of driving skills

noted that AVs could alterthe social dynamics of commuting, reducing opportunities for social interaction that currently occur during shared transport modes like school buses. Moreover, they expressed concerns about the ethical implications of AI decision-making in critical situations, reflecting a broader scepticism about the reliability and ethics of autonomous systems. The most frequently used terms from the Focus Group discussions are visually represented in the word cloud (Fig. 3) below.

Overall, these findings provide a comprehensive understanding of the teenagers' group mobility habits and their perspectives on AVs. The results underscore both opportunities and challenges in integrating AVs into the daily lives of teenagers, emphasising the need for addressing safety concerns, building trust in technology, and ensuring ethical standards in AV deployment.

4.2. Simulation results

The simulation study provided findings on the potential impacts of introducing AVs in the form of robotaxis and shuttles on teenagers' mobility. The results encompassed mode shares, trip purposes, the number of tours, tour distances, and demographic details of SAV users.

In the base scenario without SAVs, walking dominated with 63 % of trips, followed by public transport at 26 % and car passengers at 10 %. When robotaxis were introduced, there was a significant shift in mode shares: 34 % of trips were taken by robotaxi shared rides and 18 % by robotaxi private rides, reducing the shares of walking to 31 % and public transport to 5 %. With the introduction of shuttles, walking remained the most prevalent mode at 59 %, while shuttles accounted for 19 %, and public transport increased slightly to 14 %. The shifts in mobility patterns are detailed in Table 2 with the most important finding being that walking drops from 63 % to 31 % with robotaxis.

The mode choices are presented in Fig. 4.

The simulation results reflect focus group insights, where teenagers expressed a preference for flexible, on-demand transport options like AVs that offer independence from parental rides and align with their interest in innovative transport modes. The focus group insight that teenagers often combine multiple modes was incorporated into the simulation by introducing robotaxis and automated shuttles into mode choice models. The introduction of shared and private robotaxi services in the simulation corresponded with teenagers' willingness to use these services for daily commutes and long-distance travel, provided safety concerns were addressed.

The purpose of trips remained relatively consistent across scenarios. Education trips accounted for approximately 38–41 % of all trips, shopping 6 %, leisure 19–21 %, other purposes 22–26 %, and work 9–12 %. This consistency aligns with focus group feedback, indicating that travel motivations are unlikely to change substantially with the availability of AVs. The results in more detail are presented in Fig. 5.

Table 2
Mode share comparison.

Transport Mode	Base Scenario (%)	Robotaxis Scenario (%)	Shuttles Scenario (%)	Change from Base
Walking	63	31	59	–32 % / −4%
Public transport	26	5	14	−21 % / −12 %
Car passenger	10	–	–	−10 % / −10 %
Robotaxi shared rides	–	34	–	–
Robotaxi private rides	–	18	–	+18 % / –
Shuttles	–	–	19	– / +19 %
Other modes	1	12	8	+11 % / +7%

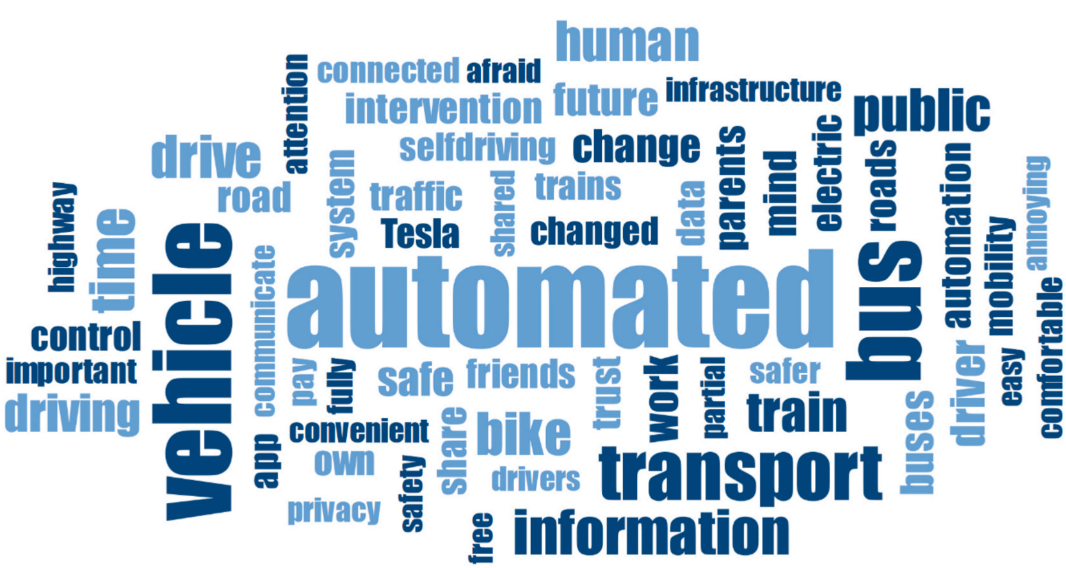

Fig. 3. Word cloud of the most frequently used words during the Focus Groups.

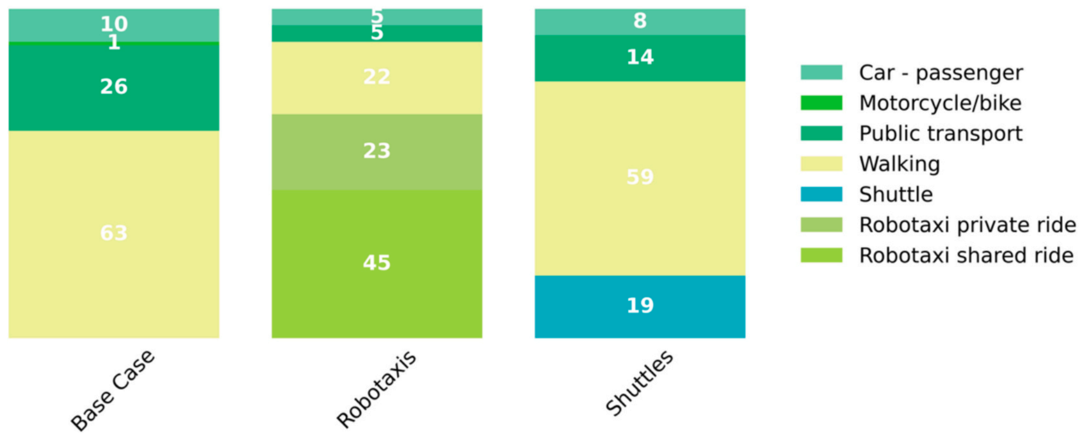

Fig. 4. Mode choices of teenagers in analysed scenarios.

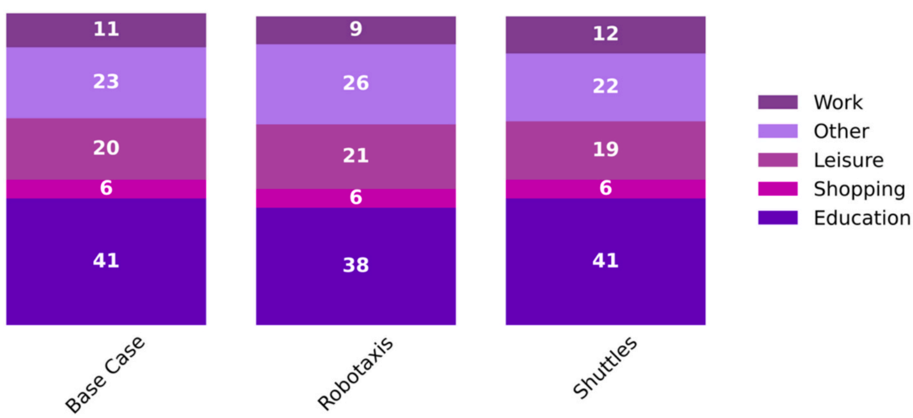

Fig. 5. Tour purposes of teenagers across analysed scenarios.

The number of tours increased slightly with the introduction of robotaxis, from 41,176 in the base scenario to 43,734. However, the number remained stable with the introduction of shuttles at 41,499. This suggested that while robotaxis may have encouraged more frequent travel, shuttles did not significantly impact the number of tours.

The trip purposes for SAV users varied, with 56 % of robotaxi trips being for education, 61 % of shuttle trips for education, 32 % of robotaxi trips for leisure, and the remaining 12 % of robotaxi trips for other purposes and shopping. Notably, 56 % of robotaxi users were girls, and 44 % were boys. This distribution skewed even further for shuttles, with 58 % girls and 42 % boys using the service. This might have reflected differences in preferences or perceptions of safety and convenience. The following Fig. 6 presents the tour purposes for journeys made with an autonomous service.

Tour distances varied across different transport modes. Walking distances decreased from 1.81 km in the base scenario to 1.55 km with robotaxis and 1.62 km with shuttles. Public transport distances increased significantly from 5.55 km in the base scenario to 8.03 km with robotaxis. In the case of shuttle implementation, the distance remained stable with a mean of 5.40 km trip length with public transport. The average distance for robotaxi shared rides was 3.95 km, for robotaxi private rides was 3.94 km, and for shuttles was 5.17 km. The

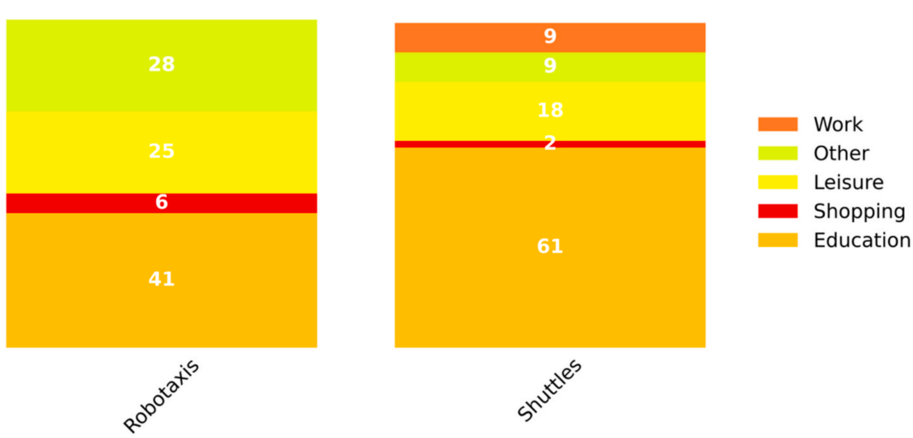

Fig. 6. Trip purposes for trips made with autonomous services.

variation in tour distances, particularly the increase in public transport distances with robotaxis, suggested that AVs could primarily be used for shorter trips, perhaps also due to the trip length pricing system.

The simulation results highlighted the potential transformative impact of AVs on teenagers' mobility. The significant shift towards robotaxis indicated a preference for the convenience and flexibility offered by these services. The slight increase in the number of tours with robotaxis suggested that enhanced mobility options might encourage more frequent travel, especially for non-mandatory purposes. However, the stability in the number of tours with shuttles indicated that, while they provided a valuable service, they might not significantly alter travel frequency.

Insights from the focus group informed several key assumptions in the simulation model. Teenagers' reliance on multimodal travel and preference for shared transport options underpinned the inclusion of both robotaxi (shared and private) and shuttle scenarios. The focus group finding that teenagers often combine multiple modes to complete their journeys was incorporated through the inclusion of new shared modes in the mode choice models: robotaxis and automated shuttles. Their generally positive but cautious attitude towards AVs, together with their willingness to use robotaxi services for daily commute and long-distance travel, balanced with safety and trust concerns, directly informed the introduction of private and shared robotaxi services and shuttles as simulated modes. The stability in trip purposes across scenarios corresponds with participant feedback that travel motivations are unlikely to change substantially with the availability of AVs.

5. Discussion

AV integration in teenagers' daily lives presents both opportunities and challenges, as evidenced by focus groups and simulation studies. Results are compared, highlighting similarities and differences, and exploring policy implications for optimising AV integration into urban transport systems for teenagers.

Both the focus group and simulation results suggest that AVs have the potential to significantly impact teenagers' mobility patterns. One of the key similarities is the preference for AVs, particularly robotaxis, due to their convenience and flexibility. In the focus groups, teenagers expressed a strong interest in AVs for the independence and enhanced mobility they offer, especially for those without a driving license. This is mirrored in the simulation results, where robotaxis account for a significant share of trips (34 % shared rides and 18 % private rides) in the scenarios where they are introduced.

The trip purposes remained consistent across both the focus groups and simulations, with education being the primary purpose for travel, followed by leisure and shopping and other trips. This consistency indicates that AVs could seamlessly integrate into existing travel patterns without disrupting the fundamental reasons for travel among teenagers.

However, there are notable differences as well. The simulation results show a marked decrease in walking and public transport usage when robotaxis are introduced, while the focus groups highlighted a continued reliance on these modes, particularly walking, due to proximity to schools and other destinations. This discrepancy suggests that, while teens today might declare their reliance on traditional modes, the introduction of an innovation could lead to negative externalities and discontinuation of reliance on active and more sustainable modes. All this will, of course, depend on practical considerations such as cost, availability, and parental preferences in real-life scenarios.

Pilot projects like Waymo's collaboration with public transport in Phoenix, Arizona (Waymo, n.d.), show how AVs can complement existing transportation systems. By integrating AVs into public transport networks, the pilot allowed for multimodal journeys, thus maintaining public transport usage while introducing AVs as a viable option for first and last-mile connectivity.

Another difference lies in the demographic preferences for AVs. The simulations indicate that girls are more likely to use robotaxis. While the focus groups did not explicitly highlight gender-based preferences, safety was a central concern for all participants, particularly regarding the reliability and trustworthiness of the technology itself. This aligns with existing research showing that girls tend to prioritise personal safety and security in their travel decisions more than boys, favouring modes that offer greater control and predictability (Karlsson et al., 2020). The observed girl's preference in our simulation is also supported by the estimated mode choice coefficients, which suggest a higher utility assigned to AVs by girls, because of the perceived safety and comfort of these modes.

AVs may be perceived as safer due to several features that directly address common travel-related safety concerns. These include potentially the ability to select verified co-passengers, real-time vehicle tracking, journey sharing with parents or guardians, and built-in emergency communication systems. Moreover, AVs can pick users up and drop them off directly at their destinations, reducing or eliminating the need to walk, transfer between modes, or wait in isolated locations. Well-lit, designated pick-up points can further enhance the perception of safety, especially during evening hours. These considerations reflect broader patterns in mobility behaviour, particularly among young women, and align with earlier research showing that parents are more willing to allow unaccompanied AV use when such safety features are available (Koppel et al., 2021; Stange et al., 2024).

Policymakers consider these gendered preferences when designing and deploying AV services. To increase acceptance and equitable use, particularly among girls and their families, services must prioritise safety features in both the vehicle and the surrounding infrastructure. This includes verified ride-matching, secure and visible waiting areas, live journey sharing, and accessible emergency support. Actively involving girls, parents, and schools in consultation processes can help tailor AV rollouts to meet real-world concerns. By doing so, AV deployment can support a safer, more inclusive mobility transition that benefits diverse user groups.

Encouraging the use of AVs presents a unique opportunity to enhance teenagers' mobility while providing significant benefits to their parents. With AVs, teenagers can travel to school independently, freeing parents from the daily responsibility of driving their children. This can lead to reduced congestion around schools during peak hours, reducing traffic and associated emissions. However, to achieve these benefits, policies should aim to balance the use of AVs with active modes and public transport to avoid a significant decline in walking and public transport usage – a result that was expected in the simulation. Integrating AVs with existing public transport networks, creating seamless multimodal transport options, and promoting walking and cycling through safe infrastructure are essential strategies to minimise the rebound effect and achieve a sustainable transport system.

Looking forward, if AVs become culturally normalised among youth, long-term behavioural adaptations can be anticipated. Having the AVs circulating around and offering convenient and independent mobility, could potentially lead to reduced motivation to learn how to drive or choose active travel modes such as walking or cycling. Additionally, the importance placed on car ownership among youth might decrease. Economically, AVs' normalisation could also lead to shifts in expenditure habits as with less need for personal car ownership, teenagers might allocate resources towards other needs rather than traditional automotive expenses. This, in turn, could affect car sales, insurance, and maintenance.

As per the results of the focus groups, building trust in AV technology is crucial. Policymakers should enforce stringent safety standards and conduct extensive public awareness campaigns to address safety concerns. This includes transparent communication about safety tests, regulations, and the ethical decision-making processes of AVs. Ensuring equitable access to AVs is also essential. Policies should focus on making AVs affordable and accessible to all teenagers, including those from lower-income households. This could involve integrating AVs into public transport systems, possibly in the form of on-demand shuttles rather than relying on possibly unsustainable private robotaxi services. The simulation results showed that providing shuttle services does not lead to a significant decline in the use of active modes, while simultaneously increasing the options available to teenagers and offering them the desired flexibility and independence. Encouraging the use of larger shared shuttle services can also help to reduce the number of vehicles on the road, mitigating potential increases in traffic congestion and environmental impact.

From a technological perspective, the development of AVs should prioritise features that address the specific needs and concerns of teenagers and their parents. Safety features must be paramount, including advanced collision avoidance systems, real-time monitoring, and secure communication channels for parents to track their children's travel. Developing user-friendly interfaces that cater to teenagers, ensuring they can easily book, navigate, and feel comfortable using AVs, is crucial. These interfaces should provide clear instructions, real-time updates, and support for multiple languages to accommodate diverse user groups.

Furthermore, AV systems should incorporate robust data privacy measures to protect users' personal information. Given the sensitive nature of tracking and transporting minors, ensuring that data is securely stored and used only for intended purposes is critical. Technological solutions should also include emergency response systems that allow for immediate assistance in case of unexpected events or malfunctions.

In conclusion, the integration of AVs into teenagers' mobility offers significant benefits but requires careful policy planning and technological innovation to address potential challenges. By balancing innovation with practical considerations, policymakers and developers can create a transport system that enhances mobility, safety, and accessibility for teenagers, paving the way for a sustainable and inclusive urban transport future.

Despite the insightful findings, this study has several limitations that should be acknowledged. Firstly, the focus group discussions, while rich in qualitative data, are limited in scope and sample size. The participants were from specific schools where children are often taken to school by a school bus, which may not be representative of all European schools. This sample composition may introduce bias, as the mobility habits and perceptions of teenagers who primarily use school buses could differ from those relying on other transport modes. As a result, the generalisability of the findings may be limited beyond similar school contexts. Moreover, the self-reported nature of the data collected in focus groups can introduce biases, such as social desirability bias, where participants may provide responses they believe are expected rather than their true opinions. The result of this bias could be seen in the discrepancy between the reported desire to continue the usage of active modes and the simulated preference for robotaxis. Secondly, the simulation model, despite its comprehensive approach, relies on various assumptions and parameters that may not fully capture real-world complexities. The accuracy of the simulation results is contingent upon the validity of these assumptions, such as the behavioural responses of teenagers to AVs and the specific configurations of AV services. Additionally, the model assumes certain characteristics and operational conditions for AVs that may not fully align with how these services will be deployed in the future. The unpredictability of technological advancements and policy changes further complicates the projections. Therefore, while the simulations provide valuable insights, they should be interpreted with caution and supplemented with continuous real-world testing and validation as AV technology evolves. Furthermore, the study's geographic focus for simulation was limited to Santander, Spain, which, while manageable for modelling, may not fully represent urban environments with different transport infrastructures, cultural attitudes, or demographics across Europe. Expanding the simulation analysis to include multiple diverse cities would enhance generalisability.

Overall, these findings provide insights into the potential benefits and challenges of integrating AVs into teenagers' daily lives. They underscore the importance of considering various factors, such as mode shares, trip purposes, travel distances, and user demographics, in the planning and implementation of AV services to ensure they meet the needs of this demographic effectively.

6. Conclusions

This study examined AV impacts on teenagers' mobility by considering focus group qualitative insights and ABM results. Focus groups revealed a reliance on passive modes (school buses, public transport, parent-driven cars). Despite strong interest in AVs for independence and robotaxis, practical factors and parental preferences influence choices.

The simulation results further highlighted the significant shift in mode shares towards robotaxis, indicating a preference for the convenience and flexibility these services offered. However, the results also showed a marked decrease in walking and public transport usage, underscoring the need for policies to balance AV usage with active modes and public transport. The analysis also revealed that girls were more likely to use robotaxis, which suggested that gender-specific preferences and safety perceptions should be considered in the deployment of AVs.

Future research could expand on these findings by exploring a more diverse and representative sample of teenagers from various geographical and socio-economic backgrounds. Increasing the size and diversity of focus group samples to include parents and guardians, would provide deeper insights into familial and social influences on teenagers' acceptance and use of AVs. Longitudinal studies could provide deeper insights into how teenagers' attitudes and behaviours towards AVs evolve over time. Additionally, research should focus on real-world trials of AV services to validate the assumptions and projections made in simulation models. This includes examining the long-term impacts of AVs on teenagers' physical activity, social interactions, and overall well-being. Further studies could also investigate the integration of AVs with existing public transport systems and the potential environmental benefits and drawbacks of widespread AV adoption.

The integration of AVs into teenagers' mobility can offer significant potential benefits, including enhanced independence, reduced school congestion, and improved accessibility for non-drivers. However, realising these benefits and preventing or limiting potential negative impacts requires careful planning and implementation of policies that promote the safe, equitable, and sustainable use of AVs. Incorporating a mixed-use approach with robotaxis and shuttles presents a promising avenue for enhancing urban mobility, where the personalised service of robotaxis complements and improves the mass transit efficiency of shuttles. It is essential to address safety concerns, build trust in AV technology, and ensure that the deployment of AVs complements rather than disrupts existing mobility patterns. By balancing innovation with practical considerations, policymakers and developers can create a transport system that enhances mobility, safety, and accessibility for teenagers, paving the way for a sustainable and inclusive urban transport future.

CRediT authorship contribution statement

Andromachi Mourtzouchou: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Ada Garus:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Rubén Cordera:** Writing – review & editing, Validation, Supervision. **Ioan Cristinel Raileanu:** Writing – review & editing, Validation, Software, Formal analysis, Data curation, Conceptualization. **Biagio Ciuffo:** Writing – review & editing, Validation, Supervision.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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