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Public acceptance of policy interventions to control transport air pollution considering nanoparticles – A study in the UK

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ABSTRACT

Ambient nanoparticles may be more harmful than PM2.5 and PM10 but currently they are not regulated. On the other hand, existing policy interventions to control PM2.5 and PM10 may not be effective enough to control nanoparticles. Therefore, there is a need to set regulations and implement policy interventions to control ambient nanoparticles emission especially from transport. However, currently there is no study on public acceptance of interventions considering nanoparticles, while such knowledge will be essential for the effective design and successful implementation of the interventions. This study thus aims to fill this research gap. An online survey was conducted in the UK (N = 482) to collect data on the general public's environmental attitudes, moral norm, awareness of and concerns about nanoparticles, and attitudes and behavioural intentions towards different transport policy interventions. Using hierarchical clustering analysis, four distinct acceptance groups were identified: the Rejective Minority; the Resistant Car dependants; the Indecisive Car-dependants; and the Supportive Environmentalists. The groups' socio-demographic and travel behavioural characteristics can help explain some of the differences in their acceptance but are not sufficient. Respondents' comments further highlighted issues of (un)fairness, distrust of government, lack of public transport and forced car ownership, and the need for information campaigns on nanoparticles. Based on these findings, group-specific barriers and opportunities were discussed and interventions suggested.

1. Introduction

Nanoparticles (or ultrafine particles (UFP), PM0.1) are particles less than 100 nanometres or 0.1 micrometres in diameter. They are less well known compared to the larger particulate matters in ambient air such as PM2.5 and PM10, which are particles less than 2.5 and 10 micrometres in diameter. Although nanoparticles only make negligible contributions to total particle mass, they dominate total particle number and surface area present in ambient air (Baldauf et al., 2016; Trechera et al., 2023). They may be more harmful than PM2.5 and PM10 due to their smaller sizes, larger numbers and larger total surface areas (Kwon et al., 2020). They can pass through lungs and into the blood stream and can potentially reach any organ in the body (Sonwani et al., 2021; Vallabani et al., 2023).

However, while concentrations of PM2.5, PM10 and many other air pollutants are regulated, for example, by the Ambient Air Quality Directives in the EU and Air Quality Standards Regulations in the UK, and recommendations for concentration limits are made by World Health Organization (2021), nanoparticles are currently not. On the other hand, existing policy interventions to control PM2.5 and PM10 may not be effective enough to control nanoparticles due to the differences in their emission sources and physicochemical properties (Air Quality Expert Group (AQEG), 2018; de Jesus et al., 2019).

Therefore, there is a need to set regulations and implement policy interventions to control ambient nanoparticles, considering their high potential health risks. Research has shown that nanoparticle emissions, especially in urban areas, arise primarily from transport-related sources (Kumar et al., 2014; Ridolfo et al., 2024). According to Paasonen et al. (2013) which modelled size segregated particle number emissions for the 28 EU countries in 2010, over 60 % of the total particle number emissions emerged from road transport, followed by 19 % from non-road transport, and about 84 % of these particles were within the size band of nanoparticles. Therefore, policy interventions in transport will be particularly important.

There is now a growing body of research on nanoparticles' emission sources, physicochemical properties, measurements, concentration modelling and mitigation methods (e.g., Abdillah and Wang, 2023; Ketzel et al., 2021; Moreno-Ríos et al., 2022; Rivas et al., 2020; Tiwari

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and Kumar, 2022), which provided essential knowledge for policy development to control nanoparticles. However, in addition to such knowledge, understanding public acceptance of the policy interventions is also key to the effective design and successful implementation of them.

Many studies have explored public acceptance of environmental and transport policy interventions such as carbon tax, road pricing, clean air zone, incentives for renewable energies and sustainable travel modes, and showed that acceptance, whether attitudinal or behaviroual, varies among different groups of the public, and can be affected by socio-demographic factors such as age and education level (Morton et al., 2021; Schmitz et al., 2019; Weiand et al., 2019), by travel behavioral factors such as travel mode and travel distance in the case of transport interventions (Anable, 2005; Schmitz et al., 2019), and more importantly, by psychological factors such as perceived problem, perceived effectiveness and perceived fairness regarding the specific interventions in question (Eriksson et al., 2006; 2008; Huber et al., 2020; Kallbekken et al., 2013), and by individual people's general environmental attitudes and moral norm (Ejelöv and Nilsson, 2020; Eriksson et al., 2006; 2008). In particular, some studies identified distinct acceptance groups, which are sub-groups of the population that show varied levels, preferences and/or motivations of acceptance (or resistance), and can allow design of tailored policy interventions that are more acceptable and effective (Anable, 2005), For example, using questionnaire survey and cluster analysis, Anable (2005) segmented a sample of day trip travellers in the UK into six distinct groups with varied degrees of potential to switch to more sustainable travel modes, characterised by travel behavioral and psychological factors such as car dependency, moral norms, social norms and environmental beliefs. Also using questionnaire survey and cluster analysis, Soto et al. (2021) identified three distinct groups among car owners in Colombia, varying in their attitudes towards sustainable transport policies and characterised by socio-demographic and psychological factors such as age, socioeconomic class, car ownership and environmental concern. In a study in Belgium, Cools et al. (2012) used Q-methodology and identified four groups among the participants varying in acceptance of and preference for different demand-restricting transport policies.

Public acceptance studies on transport interventions specifically concerning air pollution are much more limited but also suggested the influences of socio-demographic, travel behavioral and psychological factors, and the existence of distinct acceptance groups. For example, Boggio and Beria (2019) studied the results of the city-wide referendum in Milan to decide the extension of the city's pollution charge zone, and found that neighbourhoods that were more left-wing, with lower income and lower car-dependence, near city centre or at the borders of the city, and with better public transport were more likely to accept the extension. Morton et al. (2021) conducted an online survey in Scotland regarding public acceptance of Low Emission Zones. Demographic analysis of the survey results showed that female, younger individuals and individual without access to car tended to exhibit higher acceptance, while structural equation model showed that problem awareness, trust in government and policy specific beliefs such as perceived costs and benefits all had significant impact on acceptance. Mebrahtu et al. (2023) surveyed residents' perceptions of air quality and their acceptance of Clean Air Zone in Bradford. Using Latent Class Analysis, they identified three acceptance groups characterised by ethnicity and deprivation, and analysis on respondents' comments revealed that issues such as poor public transport, perceived lack of policy cohesion and unfairness can lead to lower acceptance. Based on a survey on local residents' opinions on transport interventions to mitigate air pollution in Potsdam, and using hierarchical clustering analysis, Weiand et al. (2019) identified four acceptance groups, characterised by their perceived effectiveness of and support for the interventions, concerns for air quality and environment, and travel behaviour. Results were used to identify group-specific barriers and opportunities. Relevant to acceptance, Zahedi et al. (2019) explored the public's willingness to pay to reduce air pollution from private cars in Catalonia. The study conducted a Contingent Valuation survey and found positive relationships between environmental concern and people's attitudes towards and perceived control of the payment, which contribute to higher willingness to pay, suggesting information campaign to increase concern and hence acceptance.

While types and formats of policy interventions to control transport nanoparticle emission are likely to be similar to those for the already regulated pollutants (Chen et al., 2024), and it is unlikely to have transport interventions considering nanoparticles exclusively instead of all pollutants, public acceptance of interventions that give additional consideration to nanoparticles might be different from the acceptance of interventions that aimed at regulated pollutants or air pollution more generally, given that nanoparticles are less well known, can potentially be more harmful, and may require tighter or more costly interventions, and that perceived problem and perceived intervention effectiveness are important factors that affect acceptance (Eriksson et al., 2006; 2008). However, to the best of our knowledge, currently there is no public acceptance study that focuses on or covers nanoparticles. Also, the existing studies, both on transport air pollution specifically and on environmental and transport policies more widely, confirmed the existence of distinct acceptance groups among the public which will require different policy design and implementation strategies (Anable, 2005). This suggests the possible existence of distinct acceptance groups regarding policy interventions considering nanoparticles, and the needs to explore group-specific barriers and opportunities.

Therefore, this study aims to explore public acceptance of policy interventions to control transport air pollution considering nanoparticles. Specifically, the objectives of the study are: 1) to identify distinct acceptance groups among the public based on their concerns about transport air pollution and nanoparticles emission, and acceptance of different policy interventions; 2) to compare the socio-demographic and travel behavioural characteristics of the acceptance groups, and understand how they might be affected by different policy interventions; 3) to explore group-specific barriers and opportunities and provide implications for policy intervention design.

2. Method

This study conducted an online survey in the UK to collect data on the public's awareness of and concerns about ambient nanoparticles, and their acceptance of different transport policy interventions, as well as their socio-demographic information and travel behaviours. Hierarchical clustering was used to identify groups of the public that are distinct in levels and/or types of acceptance.

2.1. Conceptualisation of acceptance

Mixed conceptualisations of acceptance have been used in the literature. While some studies defined public acceptance as attitudes towards interventions and differentiated it from public support as behavioural intentions (e.g., Dreyer et al., 2015; Jansson and Rezvani, 2019), many constructed public acceptance as a mix of attitudes and behavioural intensions (e.g., Schuitema et al., 2010; Weiand et al., 2019). In this study, we conceptualised acceptance to include both attitudes towards interventions and behavioural intentions to support them, since whether the public intend to support the interventions, in addition to their attitudes, is of key interest to our study. Specifically, attitudes towards interventions in our study consisted of perceived effectiveness and perceived fairness which are two important intervention-specific psychological factors that influence acceptance (Eriksson et al., 2008; Kallbekken et al., 2013). Behavioural intentions were measured as willingness to support specific interventions and willingness to act to support interventions more generally (Weiand et al., 2019; Eriksson et al., 2008)

In addition to attitudes and behavioural intentions, we also included

perceived problem, environmental attitudes and moral norm, which were found to be important in explaining and describing public acceptance (Anable, 2005; Eriksson et al., 2006; 2008). Perceived problem in our case indicates whether or how seriously people perceive air pollution or ambient nanoparticles to be an issue. It is a precondition for any intervention to be seen as important (Vlek, 1997). Environmental attitudes are peoples' general environmental concern and knowledge, not just limited to air quality and pollution. They are people's values associated with the environment that drive pro-environmental intentions and behaviours (Stern et al., 1999). Moral norm is the feeling of personal obligation to reduce environmental impacts. It has been shown to provide extra explanation to acceptance (Harland et al., 1999).

2.2. Online survey

The online survey consisted of six parts: Part 1: introduction to the survey; Part 2: participants' environmental attitudes, moral norm and perceived problem of general air pollution; Part 3: participants' attitudes (perceived effectiveness, perceived fairness) towards and behavioural intention (willingness to support) for some typical policy interventions to control general air pollution from transport; Part 4: a brief introduction to ambient nanoparticles covering their definition, primary sources, potential health impacts and current limitations in research and regulations; Part 5: participants' perceived problem of ambient nanoparticles, perceived effectiveness and willingness to support regarding nanoparticle interventions that are similar to the interventions asked in Part 3 but tighter, as well as timing of the intervention implementation and overall thought regarding fairness; and Part 6: participants' socio-demographics and travel behaviours. At the end of the survey, participants could leave comments to provide their own thoughts on air quality, ambient nanoparticles and interventions. All the questions in Parts 2, 3 and 5 were asked in the format of agreement to a given statement (5-point Likert scale from strongly disagree to strongly agree). The full list of the statements can be found in Appendices 1, 2 and 3.

We surveyed about general air pollution before nanoparticles because most of the public would not already have enough knowledge about nanoparticles to answer their attitudes or supportiveness directly (this was confirmed by our survey results, 3.1). Hence, the survey started with questions about general air pollution and interventions to set the context, using example interventions that are used in real world, before introducing nanoparticles and asking about tighter interventions considering them.

In Part 3 of the survey, eight policy interventions to control transport air pollution were introduced to participants (Table 1). The selected interventions covered the four general intervention categories that are commonly used in practice: bans and direct regulations; monetary incentives; infrastructure and built environment; and education and information Mattauch et al., (2016)), with five of them being "pull" and three being "push" interventions. For each intervention, a real-world example and its cost to government or individual people were shown to participants to help them to answer questions on attitudes and willingness to support. A screenshot of the survey interface of one of the interventions is shown in Fig. 1.

Table 1
Policy interventions used in Part 3 of the survey.

Policy intervention	Intervention category	Push or pull
Fiscal incentives to encourage uptake of electric vehicles	Monetary incentives	Pull
Improving charging infrastructure for electric vehicles	Infrastructure and built environment	Pull
Clean Air Zones and Low Emission Zones	Bans and direct regulations	Push
Congestion charge (applicable to all vehicles irrespective of fuel type and emission standard)	Bans and direct regulations	Push
Cheaper public transport	Monetary incentives	Pull
Better infrastructure for walking and cycling	Infrastructure and built environment	Pull
Promoting eco-driving	Education and information	Pull
Higher emission standards	Bans and direct regulations	Push

The survey obtained ethical approval at the [*Author identity removed*] (application reference: 1162) and was disseminated via a third-party survey agency and recruited participants across the UK that were representative of the UK adult population by distributing the survey based on UK census data in terms of age, gender and ethnicity. Each participant signed informed consent online before answering the survey and received £ 6 afterwards to compensate for their time. The survey was active online in June 2024 and received 516 responses in total. After removing responses that failed to correctly answer any of the three attention check questions embedded in different parts of the survey and those who finished survey exceptionally fast (3 standard deviations below the mean time), 482 responses remained and were used for analysis.

2.3. Hierarchical clustering

Hierarchical clustering was used in this study to identify distinct acceptance groups among the participants based on their responses to Parts 2, 3 and 5 of the survey (Appendices 1, 2 and 3). All statements in these parts of the survey were included in the analysis. Cluster analysis groups data points into clusters so that data points within a cluster are as similar as possible while data points between clusters are as different as possible. Hierarchical clustering is a popular method of cluster analysis. Instead of partitioning the dataset into a pre-defined number of clusters, hierarchical clustering seeks to build a hierarchy of clusters running from a single cluster containing all data points to n clusters each containing a single data point (Everitt et al., 2011), and the results can be visually presented in a dendrogram (Fig. 2). This is particularly useful for identifying public acceptance groups since the number of groups can be hard to decide *a priori*.

The analysis was conducted in R using the cluster package (Maechler et al., 2019). We used agglomerative hierarchical clustering where the clustering starts with n clusters each containing a single data point and then combine clusters in a bottom-up approach based on their similarity. The Likert-scale data from our survey was treated as numerical data, following the suggestion in Everitt et al. (2011), and Euclidean distances between data points were calculated to measure their similarity. Different linkage methods which calculate distance between clusters were tested, and the ward.D2 method in the cluster package was chosen, since the method implements Ward's (1963) clustering criterion and is the only one among the popular linkage methods that is based on a classical sum-of-squares criterion (Murtagh and Legendre, 2014), and it obtained clusters that conceptually made more sense and were well separated from each other for our dataset. The resulting dendrogram is shown in Fig. 2.

The dendrogram suggests 2, 3 or 4 could be the optimal number of groups for our dataset. While Average Silhouette method suggests 2 and Dunn Index suggests 3, we decided to have 4 groups after analysing characteristics of the resulting groups and for the purpose of making more group-specific policy implications. The decision was also supported by the suggestion in Everitt et al. (2011) that given the lack of consensus in which method to use to decide the optimal number and inconsistency in the results of different methods, informal and subjective judgement based on subject expertise might be the best method.

Once the clustering result was confirmed, the acceptance groups were profiled based on participants' responses to Parts 2, 3 and 5 of the survey, and their socio-demographics and travel behaviours compared. Participants' comments left at the end of the survey were also analysed.

Air quality control measure: Clean Air Zones and Low Emission Zones

Example: Birmingham Clean Air Zone

Vehicles that do not meet emission standard need to pay to enter: £8/day for cars, taxis and large goods vehicles; £50/day for coaches and heavy goods vehicles.

Image source: Birminghamlive. https://www.birminghammail.co.uk/news/midlands-news/birmingham-clean-air-zone-map-15969912

Based on the control measure and the example above, to what extent do you agree or disagree with the statements below? *

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Such measures are or will be very effective in reducing air pollution	☐	☐	☐	☐	☐
Considering the potential benefits, costs and impacts across society, I think such measures are fair	☐	☐	☐	☐	☐
I support or would support such measures in my local area	☐	☐	☐	☐	☐

Fig. 1. The survey interface showing one of the policy interventions.

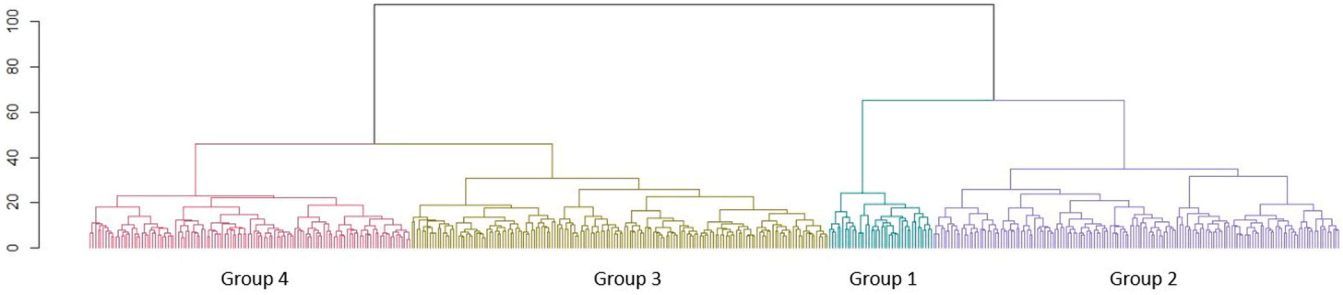

Fig. 2. Dendrogram of the hierarchical clustering results, coloured to show 4 clusters.

3. Results and discussion

3.1. Acceptance groups

Four acceptance groups were identified with respect to their environmental attitudes, moral norm, attitudes towards policy interventions to control general air pollution and nanoparticle emissions, and their behavioural intensions. Table 2 provides a summary description of the groups' profiles based on their responses to relevant statements in the survey. Group mean response to each statement can be found in Appendices 1, 2 and 3.

Group 1, the Rejective Minority, is the smallest group (only 8 % of the total respondents) and shows the lowest acceptance of policy interventions to control transport nanoparticle emissions and air pollution more generally. They are not very concerned about the environment, not guilty about causing pollution, and not willing to change their travel behaviours, or support control interventions, whether for general air pollution or considering nanoparticle emissions, especially those that would restrict car travel. They are the only group that clearly support prioritising fairness over effectiveness when considering tightened interventions to control nanoparticle emissions, which is possibly because they believe that additional interventions against private cars would be unfair. They agree that current policy interventions may not be sufficient for nanoparticles but do not think that early actions should be taken before sufficient scientific evidence is available.

Group 2, the Resistant Car-dependant, and Group 3, the Indecisive Car-dependant, together represent the majority of the general public (each making up 33 % of the total respondents). They are aware of the problems of air pollution and are concerned about the environment, but do not feel personally responsible for pollution reduction. They show similar patterns in their responses to policy interventions, favouring those promoting public transport and active modes over those restricting car travel. The difference is that while Group 3's opinions are either positive or uncertain, Group 2's are lower overall and more mixed, and show objections against car travel restrictions. This difference is fundamental in splitting the groups in the clustering analysis. As shown in Fig. 2, Group 2 would be merged with Group 1 rather than with Group 3. The difference is also important for intervention design as it decides whether a large part of the general public will consider or reject car travel restrictions which can be highly effective interventions to control nanoparticle emissions and general air pollution. Both groups believe that current policy interventions are not sufficient for nanoparticles. However, while Group 3 are likely to accept early actions to control nanoparticles, Group 2 are more uncertain.

Group 4, the Supportive Environmentalists, is the group that shows the highest acceptance of policy interventions. Accounting for 26 % of the total respondents, this cluster is characterised by high concern about the environment and moral norm in pollution reduction. They care about air pollution a lot and believe that they are under high risk of exposure to nanoparticles. They have overall very positive attitudes and are willing to support all of the policy interventions. However, it should be noted that while they are highly supportive of interventions that support electric vehicles when considering general air pollution, they rated such interventions as the least favourable when considering nanoparticles. This is possibly because the survey mentioned that even electric vehicles can still emit nanoparticles from non-exhaust emissions (Dahl et al., 2006; Kwak et al., 2014). They strongly believe that current policy interventions are not sufficient for nanoparticles, and interventions for nanoparticles should be implemented as soon as possible. This group is also the only group in which people are generally willing to change their own travel behaviours to reduce nanoparticle emission and pay higher tax to support tighter interventions.

Table 2
Profiles of the four acceptance groups.

		Group 1 (8 %) Rejective Minority	Group 2 (33 %) Resistant Car dependants	Group 3 (33 %) Indecisive Car-dependants	Group 4 (26 %) Supportive Environmentalists
Environmental attitudes and moral norm		• Not very concerned about environment and not guilty about causing pollution.	• Generally concerned about environment but do not feel responsible for pollution reduction.	• Generally concerned about environment but do not feel responsible for pollution reduction.	• Very concerned about environment and feel responsible for pollution reduction.
General air pollution	**Perceived problem**	• Are aware of air pollution and impacts but happy with local air quality.	• Believe air pollution can cause serious damage to health and care about air quality.	• Believe air pollution can cause serious damage to health and care about air quality.	• Believe air pollution can cause serious damage to health and care about air quality a lot.
	Perceived effectiveness and fairness, and behavioural intention	• Overall, negative attitudes and not willing to support, especially for interventions that restrict car travel.	• Mixed opinion. • Promoting public transport and active modes, and improving emission standards are most acceptable. • Car travel restrictions are perceived as unfair and not supported.	• Overall positive attitudes and willing to support, especially promoting public transport and active modes. • Uncertain about congestion charge and interventions that mainly benefit private car users.	• Very positive attitudes and willing to support all interventions. • Relatively less positive or supportive for interventions that mainly benefit private car users.
Nanoparticle emission	**Perceived problem**	• Limited awareness before the survey. • Less convinced that nanoparticles can be more harmful or they are under threat.	• Limited awareness before the survey. • Now believe nanoparticles can be more harmful.	• Limited awareness before the survey. • Now believe nanoparticles can be more harmful.	• Limited awareness before the survey. • Now believe nanoparticles can be more harmful and they are under threat.
	Perceived effectiveness and fairness, and behavioural intention	• Neutral attitudes towards most of the tighter interventions but not supportive of them especially those discouraging private cars. • Support fair impacts. • Not willing to change own behaviours or pay higher tax.	• Overall, positive attitudes and willing to support most tighter interventions, but not supportive of those discouraging private cars. • Neutral regarding changing own behaviours but less willing to pay high tax.	• Overall, positive attitudes and willing to support most tighter interventions, but uncertain for those discouraging private cars and those supporting EVs. • Neutral regarding changing own behaviours and paying higher tax.	• Overall, positive attitudes and willing to support all of the tighter interventions, especially those promoting public transport and active modes. Relatively less for those supporting EVs. • Willing to change own behaviours and pay higher tax.
	When to take actions	• Disagree with early actions.	• Uncertain in whether to take early actions.	• Likely to accept early regulations and interventions.	• Support early regulations and interventions.

Some characteristics are shared by all the four groups. They all had very limited awareness or knowledge of ambient nanoparticles before the survey, and now they are convinced that nanoparticles can potentially cause more serious damage to human health than the larger particulate matters that are already regulated. Despite varied levels of supportiveness across groups, they are all relatively more supportive of interventions that promote public transport and active modes within each group, both when considering general air pollution and when considering nanoparticles. They are all slightly more willing to change their own travel behaviours to reduce nanoparticle emissions than to pay higher tax to support tighter interventions.

Similar acceptance groups have been identified in the literature. For Group 1, the Die Hard Drivers in Anable (2005) and the Unconcerned Car-oriented Policy-rejecters in Weiand et al. (2019) are most comparable. They all showed strong objections to sustainable transport interventions, questioned the justifications for such interventions, and showed low concern for the environment. For Group 2 and Group 3, to some extent, they are comparable to the Complacent Car Addicts and Malcontented Motorists identified in Anable (2005), in that they also represented the majority of the sample, were very car-dependent, and the former was more resistant to car-restriction interventions while the latter was more open to them. Group 2 could also be related to the All Matters in Soto et al. (2021) who showed objections to car-restriction interventions due to their strong attachment to cars despite their environmental concern. For Group 4, similar groups are the Aspiring Env'talists in Anable (2005), the Green Conscious in Soto et al. (2021), and the Green-travel Policy-optimists and the Dedicated-cyclists & Policy-enthusiasts in Weiand et al. (2019), which all showed high environmental concern, moral norm and acceptance of sustainable transport interventions. In summary, there is a common pattern in acceptance segmentation found in the literature and in this study, that the majority of the population are car-dependent, concerned about the environment, show medium level of acceptance overall but vary towards car-restriction interventions, while the rest of the population show either very low acceptance with low environmental and moral concerns, or the opposite.

3.2. Socio-demographics and travel behaviours

While there is no substantial difference in most of the socio-demographic and travel behaviour items between the four groups, some patterns are revealed (Figs. 3 and 4). The most distinguishable group is Group 1. Compared to the other groups, Group 1 tends to be older, is majority male, is less well-educated, is of lower income status, and is shifted towards retirees. They have the highest car ownership, are the most car-dependent with 75 % of them using private cars as the main travel mode, and have the largest proportion of people living in rural and semi-rural areas. Groups 2, 3 and 4 are more homogeneous in terms of socio-demographics. Noticeable differences are that Group 4 is the most highly educated and has the highest income, while Group 3 has the highest proportion of young people and people with no children. In terms of travel behaviors, Group 4 has noticeably the lowest car ownership, and is the least car-dependent with more than half of them using public transport or active modes as the main travel mode. Both Groups 2 and 3 are fairly car-dependent, but not as much as Group 1, with around half of them using private cars as the main travel mode. Also, given that the majority of them have less than 10 km daily commute distances, are below 55 years old and in good or very good health, there is an opportunity to shift more of them from cars to public transport or active modes.

The patterns described above conform with the group profiles to some extent. Education possibly contributed to the differences in the groups' environmental attitudes and moral norm, i.e., the more people are educated, the more they are concerned about environment and feel responsible for pollution conduction. This possible association has also been found in some other studies (e.g., Anable, 2005; Odeck and Bråthen, 1997), and may have also contributed to people's choices of more sustainable travel modes as indicated in this and some other studies (e.g., Dingil and Esztergár-Kiss, 2022). Thus, it is not surprising that Group 1 has the lowest acceptance level while Group 4 has the highest. It should be noted however that the education level of our survey sample is overall higher than the UK national average (e.g., 65 % of our participants have a university degree while it is only 34 % for usual residents aged 16 years and over in England and Wales in 2021 (Office for National Statistics, 2023)). Thus, public acceptance indicated by our survey might be higher than the actual level for the UK population.

Car dependence can also possibly explain that while Groups 2 and 3 believe nanoparticles can be more harmful and tighter interventions are needed, they are reluctant to accept tighter interventions that would further restrict private car use.

Nevertheless, while socio-demographics and travel behaviours do indicate general acceptance types, they are not sufficient to explain or predict acceptance. Using acceptance group as the ordered dependent

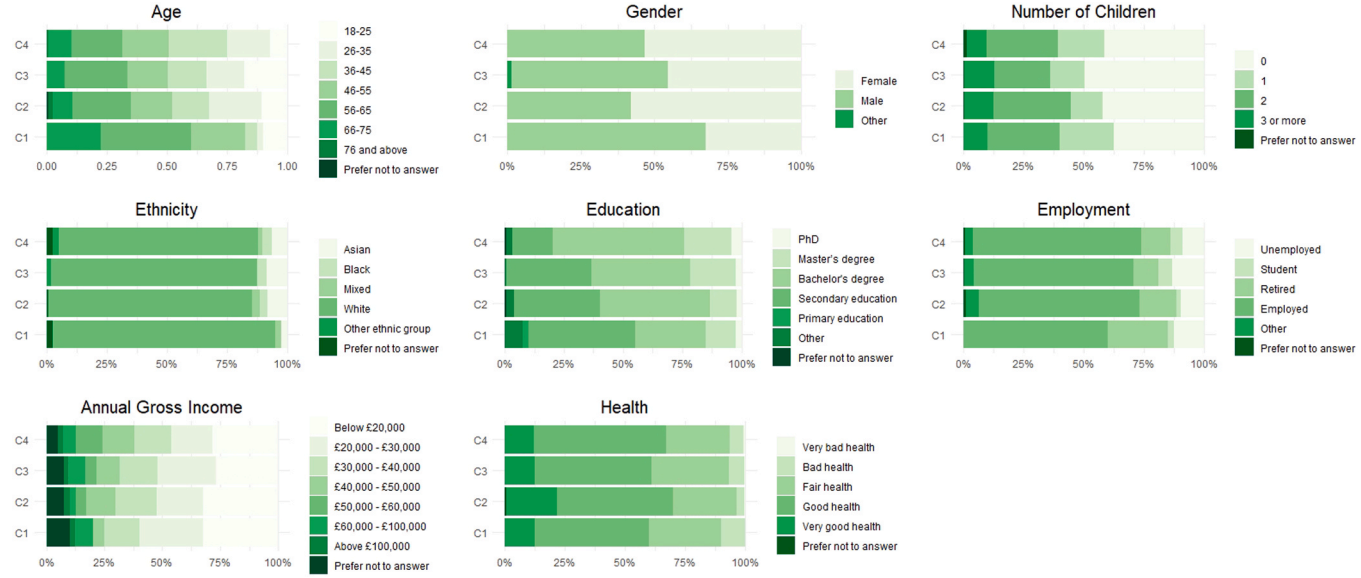

Fig. 3. Socio-demographics of the four acceptance groups (C1: Group 1; C2: Group 2; C3: Group 3; C4: Group 4).

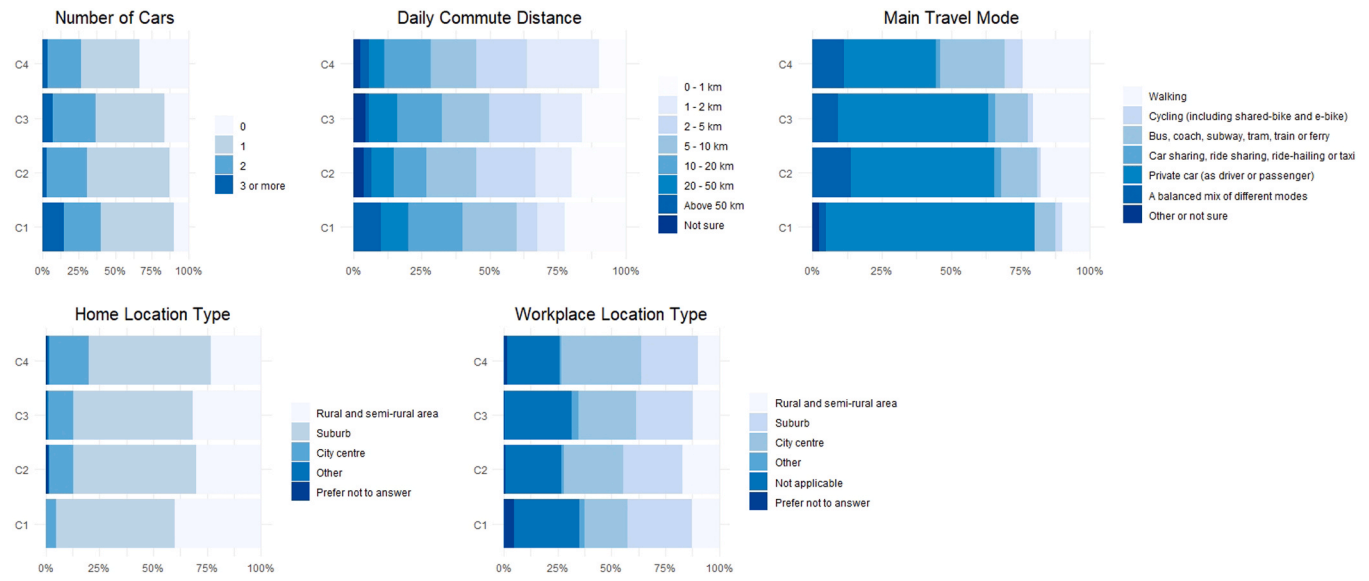

Fig. 4. Travel behaviours of the four acceptance groups (C1: Group 1; C2: Group 2; C3: Group 3; C4: Group 4).

variable and different combinations of socio-demographics and travel behaviours as independent variables, results of ordinal logistic regression (Appendix 4) show that although travel mode, travel distance, car ownership, education and income have significant impacts on acceptance, the overall model prediction powers are very low.

3.3. Respondents' comments

107 out of the 482 participants left meaningful comments at the end of the survey. These comments provided useful further information for understanding public opinion on and acceptance of the policy interventions.

One of the most frequently mentioned issues is fairness. Many from Groups 1, 2 and 3 believed that higher tax and charges on private car use will disproportionately hit already disadvantaged social groups, rural communities and local small business, as they are already financially struggling, need long commute or travel for work, and/or will not be able to afford lower-emission cars. Many of them also do not believe that EV is the solution for air pollution, and interventions that support electric vehicles will mostly just benefit rich people as electric vehicles are more expensive.

Relevant to fairness, many participants, mostly from Groups 1 and 2, expressed strong distrust of government and see tax and charges as just another way for the government to "squeeze more money from the taxpayers". Many of them do not believe the money will be used for environmental protection and one mentioned the Thames Water scandal in 2023. They do not believe the government is willing to address or is capable of addressing environmental issues and hence they do not support interventions that will come at a personal cost.

Another frequently mentioned issue is lack of public transport and forced car ownership (Curl et al., 2018), especially outside big cities. Many participants, mostly from Groups 2 and 3, commented that they need cars to get to work and/or essential services because public transport is not good enough. One participant shifted from car to public transport but is considering car again.

Instead of expressing opinions on issues, many participants, mostly from Groups 3 and 4, appreciated the knowledge and information about ambient nanoparticles introduced in the survey, and suggested that more public education and information campaigns are needed to increase public awareness of the existence and potential threats of ambient nanoparticles.

3.4. Group-specific barriers and opportunities

The profiles of the acceptance groups, together with their socio-demographic and travel behaviour characteristics, and issues and opinions highlighted in their comments, provided useful information for discussing and identifying group-specific barriers to public acceptance of policy interventions to control transport air pollution considering nanoparticles, and opportunities to enhance the acceptance. Table 3 summarises the identified barriers and opportunities, and suggests interventions that could be most acceptable and effective for each group. However, it is not to suggest that different interventions should be implemented across the public. While some soft interventions such as information campaigns could be targeted at certain groups if the groups can be identified, many hard interventions such as higher congestion charges will need to be implemented indiscriminately across the public. Nevertheless, the group-specific interventions suggested here can provide useful insights for defining priorities of interventions and designing a programme of interventions that could be most acceptable and effective depending on local or regional context.

For Group 1 the Rejective Minority, the key barriers to acceptance include lack of concerns for nanoparticles, low moral norm and very high car dependence. Their high car dependence is partly due to practical constraints as revealed by their socio-demographic and travel behaviour characteristics, but may also be partly due to their affective connections to cars as shown for similar attitudinal groups in other studies (Anable, 2005; Kandt et al., 2015). Their distrust of government can further decrease their acceptance especially for fiscal hard push interventions (Morton et al., 2021). Thus, opportunities to enhance their acceptance are overall very low. It might be necessary to build or enhance their trust in government, e.g. by more proactively communicating information about the interventions' motivation, spending, revenue and funding sources, and more effectively handling public inquiries, and in the meantime implement pull interventions such as fiscal incentives for low emission cars targeted at poorer people. Non-fiscal push interventions on cars such as speed limit and lane reduction can also be implemented to reinforce negative experience of car use to foster behavioural change without too strong resistance.

Group 2 the Resistant Car dependants also show distrust of government and high car-dependence. However, they are likely to be concerned about nanoparticles if they are aware of them, and they are open to most interventions except those restricting car use, which provide opportunities to enhance their acceptance. Information campaigns on

Table 3
Barriers to acceptance, opportunities to enhance and suggested policy interventions.

	Group 1	Group 2	Group 3	Group 4
Barriers to acceptance	• Distrust of government • Not very worried about nanoparticles • Low moral norm • Very high car-dependence • Not supportive of any interventions	• Distrust of government • High car-dependence • Lack of alternative options • Not supportive of car restrictions	• High car-dependence • Lack of alternative options	• Lack of awareness of nanoparticles
Opportunities to enhance	• Overall very low	• Likely to be convinced that nanoparticle can be very harmful • Open to most interventions	• Likely to be convinced that nanoparticle can be very harmful • Open to all interventions • Positive for early actions	• Will be very concerned about nanoparticles once aware of them • Supportive of all interventions and early actions
Suggested interventions	• Building trust in government • Fiscal incentives for low emission cars targeted at poorer people • Non-fiscal push interventions on cars.	• Building trust in government • Information campaign on nanoparticles • Education into benefits of public transport and active modes • Improve public transport • Improve infrastructure for active modes • Non-fiscal push interventions on cars.	• Information campaign on nanoparticles • Education into benefits of public transport and active modes • Improve public transport • Improve infrastructure for active modes • Push interventions on car considering distributional impacts.	• Information campaign on nanoparticles • Improve public transport • Improve infrastructure for active modes • Higher charge on car use and/or tax to fund other interventions

nanoparticles will be necessary since currently there is a lack of awareness among the public as shown in our survey results. Building trust in government and non-fiscal push interventions on cars can also be implemented for similar reasons for Group 1. In addition, interventions that improve public transport and infrastructure for active modes should also be implemented since many of the group are in forced car ownership due to lack of alternative options as revealed in their comments. However, such interventions can be expensive and very often need to be subsidised by local or national government, and a variety of funding options should be considered (Litman, 2014). On the other hand, education into benefits of public transport and active modes can also be useful to encourage those who are already able to shift away from cars.

Similar to Group 2, Group 3 the Indecisive Car-dependants also face the barriers of high car dependence and lack of alternative options. However, they show an overall higher potential of acceptance as they do not have the issue of distrust and they are open to all types of interventions including those restricting car use. They are also likely to be concerned about nanoparticles and have positive attitudes towards early actions. Thus, most interventions suggested for Group 2, including information campaigns on nanoparticles, education into benefits of public transport and active modes, and interventions that improve public transport and infrastructure for active modes, can all be useful for Group 3. In addition, fiscal push interventions on cars such as Low Emission Zone and higher vehicle tax can also be considered since this group is more open to such interventions, and charges and fines can affect the functional value of cars (Kandt et al., 2015) and thus more effectively discourage car use. However, distributional impacts of such interventions across the society should also be considered since perceived unfairness could impair this group's acceptance as shown in their comments to our survey.

Group 4 the Supportive Environmentalists already show very high acceptance. The only barrier for them seems to be the lack of awareness of nanoparticles. They will be very concerned about nanoparticles once they are aware of them and are supportive of all types of interventions and early actions. Therefore, information campaign on nanoparticles will be very important. Although they already have relatively high shares of public transport and active modes, improving public transport and infrastructure for active modes could help maintain the shares or even encourage further mode shift. In addition, since the group is supportive of fiscal hard push interventions, higher charges on cars could also be implemented to further discourage car use and fund the other interventions mentioned above.

Overall, for all the four groups, especially Groups 1, 2 and 3, pull interventions will be more acceptable than push interventions although they might not be as effective. In particular, providing sufficient public transport or other alternative options is essential for any push interventions on cars to be acceptable or to work. Implementing transport policy interventions can always be challenging, especially in our case considering nanoparticles where even tighter interventions might be needed. Any single intervention is unlikely to achieve the best results and balanced combinations of push and pull as well as hard and soft interventions are recommended (Gärling and Schuitema, 2007; Thaller et al., 2021).

4. Conclusions

This study explored public acceptance of policy interventions to control transport air pollution considering nanoparticles, taking into account the public's environmental attitudes, moral norm, awareness of and concerns about nanoparticles, and attitudes and behavioural intentions towards control interventions. With data collected from an online survey and using hierarchical clustering analysis, this study identified four distinct acceptance groups among the public in the UK: Group 1 the Rejective Minority; Group 2 the Resistant Car dependants; Group 3 the Indecisive Car-dependants; and Group 4 the Supportive Environmentalists.

Group 1 shows very low acceptance given their lack of concern, low moral norm, and negative attitudes and behavioural intentions towards most interventions. Representing the majority of the public, Groups 2 and 3 have concerns about air pollution and nanoparticles, but object to interventions that restrict car use (Group 2) or are uncertain about such interventions (Group 3). Group 4 have very high concerns and moral norm, and are willing to support all of the interventions we assessed.

The groups' socio-demographic and travel behavioural characteristics can help explain some of the differences in acceptance between groups but they are not sufficient. Analysis on participants' comments further highlighted issues of (un)fairness, distrust of government, lack of public transport and forced car ownership, and the need for information campaigns on nanoparticles.

Based on the above findings, group-specific barriers to public acceptance and opportunities to enhance acceptance were discussed and interventions suggested. Overall, pull interventions will be more acceptable than push interventions, and balanced combinations of push and pull as well as hard and soft interventions are recommended.

CRediT authorship contribution statement

Jiang Like: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Chen Haibo:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Writing – review & editing. **Liu Ye:** Methodology, Writing – review & editing.

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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.

Appendix 1. Statements in Part 2 of the survey

Statements	Factors influencing acceptance	Group mean response (1 = strongly disagree, 5 = strongly agree)			
		G1	G2	G3	G4
Air quality in my local area is very good	Problem awareness	4.1	3.3	3.6	3
I care about air quality a lot	Problem awareness	3.5	4.1	4	4.5
I and/or someone in my family are more vulnerable than the general public to air pollution	Problem awareness	2.3	2.8	2.6	2.9
Air pollution can cause serious damage to human health, as well as to wildlife and ecosystems	Problem awareness	4.1	4.7	4.6	4.9
Human activities (such as transport, manufacturing, construction, agriculture, tourism, entertainment) are causing a lot of negative environmental impacts (such as climate change, biodiversity loss, air pollution, water pollution, noise)	Environmental attitudes	3.4	4.5	4.7	4.9
I am very concerned about the negative environmental impacts of human activities	Environmental attitudes	2.7	4.1	4.2	4.7
I get a guilty conscience if I don't try to reduce negative environmental impacts caused by my activities	Moral norm	2	3.1	3.4	4.1
I get a guilty conscience if I don't try to reduce air pollution caused by my activities	Moral norm	2	2.9	3.1	3.9

Appendix 2. Statements in Part 3 of the survey

Statements		Factors influencing acceptance	Group mean response (1 = strongly disagree, 5 = strongly agree)			
			G1	G2	G3	G4
Clean Air Zones and Low Emission Zones	Such measures are or will be very effective in reducing air pollution	Perceived effectiveness	2.1	2.8	3.9	4
	Considering the potential benefits, costs and impacts across society, I think such measures are fair	Perceived fairness	1.7	2.4	3.8	4.4
	I support or would support such measures in my local area	Behavioural intension	1.5	2.1	3.7	4.4
Financial incentives to encourage uptake of electric vehicles	Such measures are or will be very effective in reducing air pollution	Perceived effectiveness	2.2	3	3.5	4
	Considering the potential benefits, costs and impacts across society, I think such measures are fair	Perceived fairness	2	2.9	3.8	4.4
	I support or would support such measures in my country	Behavioural intension	1.8	2.9	4	4.6
Improving charging infrastructure for electric vehicles	Such measures are or will be very effective in reducing air pollution	Perceived effectiveness	2.3	3.3	3.8	4.2
	Considering the potential benefits, costs and impacts across society, I think such measures are fair	Perceived fairness	2.4	3.5	4.1	4.6
	I support or would support such measures in my country	Behavioural intension	2.3	3.5	4.2	4.7
Congestion charge on all vehicles irrespective of fuel type and emission	Such measures are or will be very effective in reducing air pollution	Perceived effectiveness	1.5	2.8	3.9	4.3
	Considering the potential benefits, costs and impacts across society, I think such measures are fair	Perceived fairness	1.3	2.2	3.3	4.3
	I support or would support such measures in my local area	Behavioural intension	1.2	1.9	3.1	4.3
Cheaper public transport	Such measures are or will be very effective in reducing air pollution	Perceived effectiveness	2.9	4.4	4.4	4.5
	Considering the potential benefits, costs and impacts across society, I think such measures are fair	Perceived fairness	3.2	4.5	4.6	4.7
	I support or would support such measures in my local area or country	Behavioural intension	3.2	4.6	4.7	4.8
Better infrastructure for walking and cycling	Such measures are or will be very effective in reducing air pollution	Perceived effectiveness	2.2	3.6	4.1	4.3
	Considering the potential benefits, costs and impacts across society, I think such measures are fair	Perceived fairness	2.1	3.7	4.3	4.6
	I support or would support such measures in my local area	Behavioural intension	2	3.9	4.5	4.6
Promoting eco-driving to reduce fuel consumption and emission	Such measures are or will be very effective in reducing air pollution	Perceived effectiveness	2.3	2.8	3	3.4

(*continued on next page*)

(*continued*)

Statements		Factors influencing acceptance	Group mean response (1 = strongly disagree, 5 = strongly agree)			
			G1	G2	G3	G4
	Considering the potential benefits, costs and impacts across society, I think such measures are fair	Perceived fairness	2.2	2.9	3.1	3.7
	I support or would support such measures in my local area or country	Behavioural intension	2.1	3	3.1	3.9
	Such measures are or will be very effective in reducing air pollution	Perceived effectiveness	3	3.9	4.3	4.4
Higher emission standards for vehicle manufacturers and fuel products to comply with	Considering the potential benefits, costs and impacts across society, I think such measures are fair	Perceived fairness	2.7	3.5	4.1	4.5
	I support or would support such measures in my local area or country	Behavioural intension	2.6	3.7	4.1	4.6

Appendix 3. Statements in Part 5 of the survey

Statements	Factors influencing acceptance	Group mean response (1 = strongly disagree, 5 = strongly agree)			
		G1	G2	G3	G4
Nanoparticles can cause more serious damage to human health than the larger particulate matters that are already regulated (such as PM2.5, PM10).	Problem awareness	3.7	4.2	4.2	4.3
I believe I (or my family) live or work in an area with high risk of exposure to nanoparticles	Problem awareness	2.3	3.4	3.2	4
Current policies and measures to control air pollution are NOT sufficient for nanoparticles	Problem awareness	3.9	4.5	4.4	4.7
We should wait for more scientific evidence on nanoparticle impacts before taking additional actions to control nanoparticle emissions	Timing	4	3.3	3	2.5
Considering nanoparticles' potential threats, new air quality regulations that are tighter than current ones should be implemented as soon as possible.	Timing	2.9	3.7	3.9	4.5
In areas of high nanoparticle exposure risk, local control measures should be implemented as soon as possible even without regulations established by central government.	Timing	2.4	3.2	3.6	4.2
Implementing tighter measures that discourage private car use (such as higher vehicle tax, more congestion charge zones or low emission zones) will be very effective in reducing nanoparticle emissions.	Perceived effectiveness	1.9	2.8	3.4	4.1
I will support tighter measures that discourage private car use (such as higher vehicle tax, more congestion charge zones or low emission zones) to be implemented from next year in my local area or country to reduce nanoparticle emissions.	Behavioural intension	1.4	2.4	3.3	4.2
Implementing more measures that support uptake of electric vehicles (such as lower vehicle tax, more investment on charging points) will be very effective in reducing nanoparticle emissions.	Perceived effectiveness	2	2.8	3.3	3.5
I will support more measure that support uptake of electric vehicles (such as lower vehicle tax, more investment on charging points) to be implemented from next year in my local area or country to reduce nanoparticle emissions.	Behavioural intension	1.7	3	3.6	4
Implementing more measures that promote public transport (such as cheaper tickets, more investment to improve services) will be very effective in reducing nanoparticle emissions.	Perceived effectiveness	2.7	4.1	4.1	4.3
I will support more measures that promote public transport (such as cheaper tickets, more investment to improve services) to be implemented from next year in my local area or country to reduce nanoparticle emissions.	Behavioural intension	2.9	4.3	4.3	4.6
Implementing more measures that promote walking and cycling (such as more investment on walking and cycling infrastructure, planning for more services and amenities to be within walking or cycling distances) will be very effective in reducing nanoparticle emissions.	Perceived effectiveness	2.8	4.2	4.3	4.7
I will support more measures that promote walking and cycling (such as more investment on walking and cycling infrastructure, planning for more services and amenities to be within walking or cycling distances) to be implemented from next year in my local area or country to reduce nanoparticle emissions	Behavioural intension	2.3	4.1	4.3	4.8
Having more public education and campaigns about ambient nanoparticles will be very effective in reducing nanoparticle emissions.	Perceived effectiveness	2.4	3.7	3.8	4.1
I will support more public education and campaigns about ambient nanoparticles to start from next year in my local area or country to reduce nanoparticle emissions.	Behavioural intension	2.4	3.8	4	4.6
Implementing tighter vehicle emission standards for vehicle manufacturers and fuel products to comply with will be very effective in reducing nanoparticle emissions.	Perceived effectiveness	2.7	3.7	4	4.1
I will support tighter vehicle emission standards for vehicle manufacturers and fuel products to comply with to be implemented from next year in my local area or country to reduce nanoparticle emissions.	Behavioural intension	2.4	3.6	4	4.4
I am willing to change my travel behaviour to reduce nanoparticle emissions, even though it may cause inconvenience or be more expensive.	Behavioural intension	1.4	2.8	3.2	4
As a taxpayer, or if I was a taxpayer, I would be willing to pay higher tax to support tighter measures to reduce nanoparticle emissions.	Behavioural intension	1.2	2.3	2.9	3.7
Private car users should pay more (for example, higher car and fuel prices, vehicle tax, road charge) to support tighter measures to reduce nanoparticle emissions.	Fairness	1.1	2.2	3	3.8
If a tighter measure can effectively reduce nanoparticle emissions in my local area but will disproportionately benefit and disbenefit different people, it should NOT be implemented	Fairness	4.1	3.6	3.3	2.9
Having learned (more) about ambient nanoparticles, I am now more supportive of air quality control measures overall.	Behavioural intension	2.4	3.8	4.1	4.6

Appendix 4. . Results of ordinal logistic regression

Variable	Variable category	Coefficient					
		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Acceptance group (dependent variable)	Group 1	-2.201**	-2.193**	-2.351**	-2.345**	-2.474**	-2.364**
	Group 2	-0.010	-0.014	-0.164	-0.170	-0.317	-0.207
	Group 3	1.607**	1.593**	1.447**	1.431**	1.265**	1.373**
Travel Mode	Public transport	0.702*	0.671*	0.675*	0.647*	0.580*	0.605*
	Active mode	0.572*	0.551*	0.577*	0.559*	0.501	0.518*
	Mixed	0.408	0.374	0.391	0.356	0.308	0.316
	Car	-	-	-	-	-	-
Travel distance	1–2 km	1.022**	1.016**	1.010**	1.005**	0.991**	1.007**
	2–5 km	0.550	0.527	0.535	0.512	0.466	0.484
	5–10 km	0.459	0.442	0.400	0.382	0.440	0.438
	10–20 km	0.707*	0.660*	0.661*	0.611	0.579	0.597
	Above 20 km	0.274	0.269	0.195	0.185	0.171	0.152
	0–1 km	-	-	-	-	-	-
Household car ownership	1 car	-0.629*	-0.679*	-0.611*	-0.663*	-0.717**	-0.640*
	2 cars	-0.381	-0.454	-0.366	-0.446	-0.529	-0.453
	3 or more cars	-0.441	-0.501	-0.452	-0.519	-0.665	-0.569
	No car	-	-	-	-	-	-
Age	26–35	0.059	0.066				
	36–45	0.344	0.358				
	46–55	-0.070	-0.060				
	56–65	-0.088	-0.093				
	66 and above	0.027	0.022				
	18–25	-	-				
Gender	Female	0.095	0.120				
	Male	-	-				
Ethnicity	Asian	-0.243	-0.231	-0.180	-0.161		
	Black	-0.231	-0.236	-0.251	-0.244		
	Mixed	-0.834	-0.853	-0.904	-0.916		
	Other	0.830	0.815	0.850	0.845		
	White	-	-	-	-		
Number of children	1 child	0.025	0.025				
	2 childern	-0.015	-0.029				
	3 children or more	0.182	0.180				
	No children	-	-				
Higher education	No	-0.634**	-0.595**	-0.636**	-0.597**	-0.583**	-0.584**
	Yes	-	-	-	-	-	-
Employment	Unemployed	-0.519	-0.232	-0.544	-0.246	-0.231	
	Retired	-0.347	0.048	-0.426	-0.034	0.021	
	Student or other	-0.086	0.113	-0.131	0.074	0.203	
	Employed	-	-	-	-	-	
Annual income	£ 20,000 - £ 30,000	0.055	0.066	0.058	0.068	0.047	0.076
	£ 30,000 - £ 40,000	0.218	0.213	0.229	0.219	0.106	0.149
	£ 40,000 - £ 50,000	0.459	0.473	0.524	0.532	0.477	0.513
	Above £ 50,000	0.671*	0.675*	0.713*	0.708*	0.682*	0.715*
	Prefer not to answer	-0.397	-0.362	-0.360	-0.328	-0.257	-0.195
	Below £ 20,000	-	-	-	-	-	-
Health	Bad	0.471	0.463	0.475	0.465		
	Fair	0.193	0.203	0.156	0.161		
	Good	-	-	-	-		
Home location	Rural	0.028		0.002			
	Suburban	-0.058		-0.080			
	Urban	-		-			
Workplace location	Rural	-0.265		-0.278			
	Suburban	0.032		0.036			
	Not applicable	0.415		0.432			
	Urban	-		-			
Model performance							
Model fitting	Chi-Square	79.521	76.054	76.177	72.312	66.156	64.993
	df	40	35	31	26	20	17
	p value	0.000	0.000	0.000	0.000	0.000	0.000
Pseudo R-Square	Cox and Snell	0.152	0.146	0.146	0.139	0.128	0.126
	Nagelkerke	0.165	0.158	0.158	0.151	0.139	0.137
	McFadden	0.064	0.061	0.061	0.058	0.053	0.052

** Significant at 0.01 level
* Significant at 0.05 level

Data availability

Data will be made available on request.

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