Determinants of low-carbon transport mode adoption: systematic review of reviews

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Abstract

Urban transport provides access to multiple services, structures and impedes daily life of residents, and translates into wellbeing considerations, sustainability impacts, and GHG emissions. Thus motivated, multiple disciplines, ranging from psychology to urban planning, are invested in understanding the potential for transitioning to low-carbon and sustainable urban transport systems. While each discipline has carved out a growing body of knowledge, a consistent cross-disciplinary understanding of psychological, sociological, and urban form determinants of urban mobility choices is, perhaps surprisingly so, still lacking. Here, we systematically review the reviews of several strands of literature and lay out the evidence for individual, social, and infrastructure level factors pertinent to urban mode choice. Synthesizing the results from 75 review papers, we find that all three dimensions (individual, social, and infrastructure) unambiguously interfere with mode choice. Individuals are most motivated to shift modes, if they are well informed, if personal norms match low-carbon mode use, and, most importantly, if they perceive to have personal control over decisions. Perceptions about common travel behaviour (descriptive social norms), especially if supported by perceived normative beliefs of others (injunctive norms), are highly influential to support mode shift. However, the overall margin of shift as induced by individual and social settings remains limited. Instead, the infrastructure factors explain large differences in mode choice. New shared mobility modes, and teleworking and shopping, add a long tail to modes chosen, but are no game changer. We conclude that a transition to low-carbon mobility requires low-carbon infrastructure, which leverages enthusiastic individuals’ concerns and empowers them for mode change, and that address safety concerns prevalent especially in cities of the Global South. The mode shift to low-carbon option can then be sustained and enhanced by social influence in the form of collective social norms.

1. Introduction

The importance of designing low-carbon urban transport systems in tackling urban carbon emissions is gaining prominence. Urban transport generates about 6% of global anthropogenic GHG emissions (ca. 3 Gt CO₂/yr.) (Creutzig et al. 2016) and is growing in absolute terms with ongoing rapid urbanization. However, urban transport solutions may also help to overcome the transport sector roadblock to climate change mitigation (Creutzig et al. 2015). At the same time, urban car mobility is associated with several local sustainability challenges, including air pollution, congestion, and noise (Bongardt et al. 2013). Unsurprisingly, addressing urban transport issues is a topic of broad public engagement, as it concerns everyday behaviour, and is experienced both actively and passively by nearly everyone. Urban mobility is more intertwined with human behaviour and everyday life than most other sectors (Van Acker et al. 2016).

Promoting non-car alternatives, from public transport to cycling, is an important element in...
designing a low-carbon transport system. Modal shift constitutes an affordable opportunity to rapidly reduce GHG emissions at much shorter time scales than achievable by a transition to electric vehicles alone (Hill et al 2019). Alternatives to car use can also deliver significant co-benefits, especially in the social domain. Transport system prioritizing non-car alternatives can provide greater accessibility for different social groups (Lucas et al 2001) and can lead to greater economic activity (Bhatta and Drennan 2003). Furthermore, these alternative modes are associated with better health outcomes and increased well-being (Woodcock et al 2009).

Our understanding of modal shift from cars to sustainable transport modes remains surprisingly fragmented. How do people decide on certain travel modes? What are the different factors that determine these choices? What is the relative importance and inter-linkages between these different factors? In part, these gaps can be attributed to the fact that transport mode choice is a complicated, cross-disciplinary issue. As a result, despite significant advances, the literature is divided across different disciplines. Many of the related disciplines do not have an established culture of aggregating knowledge in a systemic manner (Beelmann 2006, Minx et al 2017).

In this paper, we synthesize a diverse body of literature on the reduction of car use and uptake of alternative low-carbon transport modes for urban mobility. Our research question is: what are the main determinants of travel mode choice and how these different determinants are linked to each other? To answer our research question, we conduct a systematic review of reviews on low-carbon transport mode uptake and modal shift, focussing on urban settings, and surveying literature from different fields, including psychology, economics, sociology and urban planning.

Given the challenges involved with tackling such a broad array of literature, we first propose a simple framework for travel mode choice in general. This framework broadly consists of three different categories (i) individual factors (both material and psychological), (ii) social factors, and (iii) infrastructure-related factors. The framework allows us to extract information from review papers on transport mode choice and organize this information in a meaningful way. We also use this framework to guide our literature search. Our search strategy is as follows. In the first step, we conduct a literature search for different review studies related to determinants of travel mode choice in urban settings. Based on diverse data banks we conduct a systematic review of reviews (that is, we use keywords for systematically identifying all relevant reviews conducted on main determinants of using non-car alternative transport modes). After identifying relevant review papers, we systematically extract the information related to different categories of determinants and their influence on travel mode choice.

We organize our results based on different categories of determinants and their importance for different travel modes. Concerning low-carbon travel mode use in general, we find that transport infrastructure factors are associated with the biggest gains in increased use of these travel modes. Dedicated infrastructure for low-carbon modes, system coverage and connectivity tend to follow in the order of importance. The evidence for built environment factors remains mixed and dependent on specific transport mode. Low-carbon transport mode usage exhibits spatial and social network effects. This indicates some role for social influence. Indeed, meta-reviews suggest that both the perception of others’ travel behaviour (descriptive norms) as well as perceived normative beliefs of others about travel behaviour (subjective norms) are associated with higher use of low-carbon transport modes. However, some studies argue that at least in the case of biking, social signalling aspects such as social status and social identity combined with subjective norms tend to be more important than just descriptive norms. In terms of individual-level factors, (control) beliefs are generally highly correlated with low-carbon transport mode choice. Personality related aspects such as personal values are also associated with mode choice, however, their impact tends to be significantly lower than that of beliefs. Overall, individual-level factors show a greater correlation with intentions to use low-carbon travel modes rather than reported behaviour. Indeed, this is commonly referred to as the ‘intention-behaviour gap’ in the related literature. Our review suggests that there is some evidence that some infrastructure level factors can address specific aspects of this gap in certain conditions.

In addition to above-mentioned factors, and for specific transport modes, we find that reducing car use shows low correlation across different categories in the short term. Only street-design and accessibility measures are highly correlated with lower car use. Other factors such as job or population density and land-use diversity tend to show very low correlation values. Even infrastructure provision seems to have a larger impact only in the longer run, possibly combined with or channelled through social norms and cultural change. This is also true for changes in prices and/or travel time, as the fuel and time elasticity values for car use tend to smaller in the short-run, however longer-run values are typically higher suggesting that these factors play a more important role in shaping behaviour over time. Similarly, subjective norms and personal values show a medium-to-small correlation with car use.

Higher transit use is correlated with built environment factors such as street design and accessibility. The price and time elasticity values for public transit (PT) indicate that while higher prices can shift commuters to other transport modes, low prices do not necessarily bring more car users. Indeed,
there is some substitution across low-carbon modes on this metric. Transport system attributes such as speed and frequency of transit are important for both attracting car users as well as retaining current public transit users. Soft attributes of transport systems (such as service quality perceptions) tend to be associated with relatively marginal gains. Furthermore, individual-level factors such as beliefs, demographic factors can often act as a barrier to greater PT use. In most of these cases, public transit system factors need to be either altered or enhanced to attract these users.

Bike-use and walking show greater association with individual-level factors such as demographics and beliefs about safety. This is complemented by greater evidence of bike choice being influenced by social learning and social influence processes. Certain amenities at destination (such as shower, changing facilities, etc) and weather conditions are also specifically more important for biking than any other transport mode. Built environment factors are especially important for walking. Indeed, higher incidence of walking is often highly correlated with these factors such as higher density, and land-use diversity.

Our paper contributes to the existing literature in several ways. First, we combine evidence from several different strands of literature (economics, psychology, and urban planning among others), thereby providing a more comprehensive view of empirical evidence on determinants of travel mode choice. The literature from these different disciplines allows us to incorporate different types of determinants. This complements existing reviews that focus on one particular aspect of travel mode choice. Secondly, we explore the potential inter-linkages and nonlinearities related to these different factors and their impact on travel mode choice. This provides a better understanding of entry points and limitations of potential interventions in transport systems for promoting low-carbon transport modes.

2. Framework for explaining travel mode choice

Disciplines differ in their understanding of transport mode choice. Urban planners understand transport mode choice as being determined by the planning process and focus on the built environment. Psychologists interpret travel mode choice as a result of cognitive mechanisms that are explained by frameworks such as habit formation (automatic behaviour), norm activation model, and theory of planned behaviour. Social psychologists and sociologists highlight the role of social norms, mobility culture and social networks in determining transport mode choice as a social process. Rational choice theory in its various iterations is the most prominent framework in economics. In turn, economists view transport mode choice as resulting from rational choice based on calculating utilities, weighing costs and benefits of different transport modes. They view monetary and time costs as the most important factors in determining transport mode choices.

While, none of these perspectives claims completeness, or exclusivity, due to disciplinary boundaries these different perspectives end up looking at pieces of a puzzle rather than providing the complete picture. Therefore, even though each discipline consolidates their research on the underlying mechanisms, understanding how they interact with each other and their relative importance for travel mode choice is lacking.

We propose the framework for understanding travel mode choice to bring together these different perspectives in a simple manner. Figure 1 presents the main elements of the framework. The purpose of the framework is to provide a general guideline to link a disparate set of related concepts and give them a contextual understanding (to potentially assign categories where none was explicitly considered). Our framework consists of three main categories (i) (both material and psychological) individual-specific factors, (ii) social-level factors, and lastly (iii) (both human and natural) infrastructure-related factors. We propose that travel mode choice is a function of factors related to these three broad categories. In addition, we consider ‘information’ as a separate overarching factor which connect these three broad categories and also plays a part in transport mode choice. We add a component on habits and path dependency which indicates how choices in past shape future options.

The framework consists of three main categories: individual-level factors (a), social level factors (b), and infrastructure-level factors (c). In Figure 1, we provide a schematic representation of different categories considered in our review. Full description of each of these categories is given in the supplementary appendix (section A.1) (available online at stacks.iop.org/ERL/15/103002/mmedia).

In terms of how these categories are related to travel mode choice, we are interested in three different types of relationships. First, direct effects, which consider the relationship between variables from one category (say individual factors) and how they impact travel mode choice. In Figure 1 these effects are depicted by directional arrows from categories to travel mode choice. In terms of prevalence, this is likely to be the most important type of effects considered in this review. Secondly, we are also interested in conditional effects, which reflect how direct effects depend on other categories. For instance, the impact of individual-level factors on travel mode choice may vary depending on social or infrastructural level factors. Lastly, we also consider interaction effects, i.e. how one category of variables impact other categories. A typical example of this is that individual-level factors such as demographics etc can
shape infrastructure level factors and vice versa. In figure 1, these effects are depicted as dotted lines linking one category of variables to others.

3. Methodology

3.1. Search strategy

The review process is carried out in different steps. Figure 2 explains these different steps. First, we search for literature reviews related to the adoption of low-carbon transport modes. Secondly, and only in case we do not find any literature review related to one of the determinant categories, we planned to conduct our own literature review on issues related to that particular category. As we were able to find reviews related to different aspects outlined in our framework, we did not conduct any category-specific reviews.

The review was conducted to broadly comply with the Roses guideline (for more information about the roses guideline see Haddaway et al. 2018). The systematic search was conducted between April-May, 2019.

We design our search queries for Web of Knowledge and Scopus. Search terms and Boolean combinations are customised to accommodate differences across platforms. The search is conducted in two stages. In the first part, we look at literature reviews related to the adoption of low-carbon transport modes across disciplines and categories. For this primary search, we use variations of three sets of keywords. These include transport modes (e.g. ‘bicycles’, ‘modal choice’), type of literature review (e.g. ‘meta-analysis’) and terms excluded from the search (e.g. ‘nanoparticle’). Full list of keywords is given in the supplementary appendix A (table A.1).

3.2. Study selection and inclusion/exclusion criteria

We apply hierarchical screening of query results starting from titles to abstracts/keywords to the full text. We include papers that:

i. review literature on adoption of low-carbon transport modes. This means we do not include original studies but only papers which collect available evidence base. Given the fact that some areas of research may not be established enough to have comprehensive literature synthesis, we use an expansive definition of review which includes limited literature reviews.

ii. focus on the causes of low-carbon transport mode uptake. More specifically, we are interested in studies which try to explain why low-carbon transport modes are used. We do not consider studies which are primarily related to the benefits of using these low-carbon transport modes.

iii. provide at least one quantitative/qualitative measure of an association between one of the
underlying mechanism and a measure of low-carbon mode use.
iv. were published in English.

We exclude reviews that only look at non-urban transport (such as holiday travel, marine travel etc.). No limitations were set on study design or other socio-demographic population characteristics, however, we restrict our search to review papers published in or after 2000.

3.3. Data extraction
Our data extraction strategy is divided into two parts. In the first stage, we look at underlying literature reviews and categorize them in one of the 2 categories (meta-analysis or traditional review). The main differentiation lies in the level of evidence aggregation for different types of literature reviews. In the case of systematic meta-reviews, the evidence presented is aggregated across several different studies. On the other hand, traditional reviews highlight important/interesting results from individual studies. Therefore, extracting information across these different review types requires different criteria. For evidence, which relies on literature reviews with some degree of evidence aggregation, we take the estimates from the review itself. In the case of evidence from traditional or narrative reviews, where findings from single studies are presented, we go back to the original study. For original studies, we differentiate between quantitative and qualitative studies. This distinction is important for the data extraction. The second step consists of two components: extracting information and judging the quality of information. For meta-analysis studies, we extract all information relevant to different categories of our framework, including information related to demographics etc. For traditional reviews, we go back to the original studies and extract information from the original study that is relevant to the category reported in the literature review.

3.3.1. Relationship strength ratings
Relationship strength rating indicates the level of association between the interested independent variable and mode choice variable. These ratings are calculated separately for different types of result indicators. Table 1 provides a summary of different result indicators used in different literature streams (more detailed description is given in supplementary material section A.3.1). In psychology and individual differences literature the guidelines are relatively straight forward and consistent (Cohen 1992) (Gignac and Szodorai 2016). Following these commonly accepted guidelines of effect size description, we classify $r$ values on a scale of 1–5 with corresponding values ($0.1 \leq r < 0.2$, $0.2 \leq r < 0.3$, $0.3 \leq r < 0.5$ and $r > 0.5$ are to be considered very weak, weak, medium, strong and very strong in magnitude).

For regression analysis, such a standardized convention is not available as effect size depends on coefficient and units of the variable. Therefore, in such cases, we rely on the judgement of the authors of the underlying studies, and comparison across different effect size values found in the related literature. Lastly, elasticity measures have relatively straight forward interpretation as they are dimensionless. However, here again, there is no standard convention on interpreting an elasticity value as low or high. As a result, we rely on the judgment of the authors of the underlying studies and comparison across different effect size values found in the related literature. For each relationship between relevant independent variable and travel mode choice variable covered in a review paper, we give a score between 1–5, to indicate the strength of the relationship between the independent variable and travel mode choice variable. Although based on criteria laid out above, these scores necessarily require subjective judgement and should be understood as such.

3.3.2. Confidence scale
We use IPCC’s recommended confidence scale when reporting on the strength of the evidence (Mastrandrea et al 2010). The confidence scale is based on a two-dimensional representation of Evidence (robust, medium and limited) and the degree of scientific agreement (high, medium and low). We evaluate two different elements when evaluating the quality of evidence: (i) study evaluation, and (ii) related ‘evidence’ evaluation. The evaluation criteria for both these elements differ depending on the study type (more detailed description is given in supplementary material section A 3.2). While being based on the criteria outlined above, given the variation across study types, the confidence scale ratings are based on our subjective judgement and should be understood as such.

4. Results
At the end of our search process, we can identify around 75 reviews which fulfill all the necessary conditions (supplementary appendix B for details about these studies). Thematically, most review studies are linked to infrastructure factors in one way or the other (59 reviews), whereas social factors are lacking in most cases (only 11 review studies). Individual-level factors are also relatively well represented with 32 reviews dealing with these factors. Most of the reviews cover studies from North America (particularly US and Canada), Europe (mainly the UK, Scandinavian countries, Germany and Netherlands) and Australia. Only 20% of the reviews contain at least one study from Asia or Africa. Asian cases are mostly represented by Japan, South Korea, Taiwan, China and India. In terms of income level, none of the reviews covers low-income countries. Only 15% of reviews contain
at least one paper from lower-middle-income countries and only 20% have at least one paper based on higher-middle-income countries. In other words, the vast majority of the reviews are based on papers from high-income countries. Topically, only reviews for transport system-related factors are based on a decent variety of international case studies. For individual and social factors, almost all review papers are based on high-income countries. This is also largely true for reviews on built environment factors (with some exceptions).

Mobility outcomes considered here are those relevant for daily travel decisions (mode choice, and trip choice) and possibly long term decisions (car/bicycle purchase) that are known to influence travel. For this section, we first present the results from directs effects separately for each category of framework variables. After this, we present the conditional and interaction effects combined.

4.1. Direct effects

Figure 3 gives a summary of the most important factors resulting from our literature review.

4.1.1. Individual-level factors

We divide individual level factors in three subcategorizes: behavioral and cognitive factors, habits, and socio-demographic factors. Figure 4 summarizes the evidence for most important individual-level factors, including the assessment of relationship strength and confidence scale rating.

4.1.1.1. Behavioral and cognitive factors

The analysis of behavioural factors is guided by psychological theories, with 15 different frameworks identified (Chng et al 2018). The Theory of Planned Behaviour and/or the Norm Activation Model is employed in at least half of the cases (50% of the total studies). The remaining theories are only applied in a limited number of studies (most are only applied in one or two studies). The similarity in frameworks, reflecting also the uniformity of reported variables, facilitates comparison across studies and paves the way for in-depth meta-reviews.

In the domain of travel-mode choice, three meta-analyses on the determinants of individual travel mode intentions and behaviour have been published (Gardner and Abraham 2008, Hoffmann et al 2017, Lanzini and Khan 2017). Two meta-analyses (Gardner and Abraham 2008, Lanzini and Khan 2017) also study the determinants of intention to use particular travel mode in addition to travel mode choice in itself.

Intentions are significant and substantive predictors of the individual driving. But whereas Lanzini and Khan (2017) report an averaged pooled car use—intention correlation of $r_{+} = 0.83$, the averaged pooled car use—intention correlation reported by the other two meta-analyses is $r_{+} = 0.53$, and $r_{+} = 0.50$ respectively (Gardner and Abraham 2008, Hoffmann et al 2017). Because the reported confidence intervals do not cover these huge differences, they cannot be attributed to chance influence. The results reported by Lanzini and Khan (2017) are based on a systematically different information set than the quite similar results reported by the two other meta-analyses.

Attitudes are one of the most frequently included item in studies on individual level factors. As with intentions, there is significant disagreement, in terms of magnitude of the association, between the three meta-analysis. Hoffmann et al (2017) report low correlation between car use and attitudes towards car...
use ($r_+ = 0.22^{***} ; k = 38 ; n = 4647$) as well as non-car options ($r_+ = -0.23^{**} ; k = 3 ; n = 812$). Whereas, Lanzini and Khan (2017) report medium correlation between car use and attitudes to driving ($r_+ = 0.41^{***} ; k = 15 ; n = 4290$) and non-car options ($r_+ = -0.36^{***} ; k = 7 ; n = 3283$). There is greater agreement on medium level association between attitude towards non-car options and non-car travel mode usage ($r_+ = 0.31^{***} ; k = 12 ; n = 13282$) (Lanzini and Khan 2017).

Beliefs are key to explain travel behaviour. The results of all three meta-analyses show that as proposed by the theory of planned behaviour (TPB), perceived behavioural control (PBC), a person’s expectation that performance of the behaviour is within her control, is significant and substantive predictors of individual car use. According to best estimates, the relationship between car use and PBC related to car use is medium-to-strong ($r_+ = 0.39^{***} ; k = 9 ; n = 1605$). This is similar for PBC related to non-car and its association with car and non-car use, although as expected the direction of effect is opposite to each other. For other types of beliefs, the meta-analysis focuses on beliefs about the ascription of responsibilities- attributing own action to different social/environmental outcomes. Both meta-analysis studying this find no significant effect of ‘ascription of responsibilities’ on car use (Hoffmann et al 2017, Lanzini and Khan 2017), although Lanzini and Khan (2017) report a significant but small effect of ‘ascription of responsibilities’ on non-car use ($r_+ = 0.22^{***} ; k = 4 ; n = 1746$).

Awareness is less relevant in explaining the observed mode choice. Behavioural processes commonly studied include ‘problem awareness’ and ‘awareness of consequences’. In both cases, there are differences between the two major meta-analyses. Lanzini and Khan (2017) find that the association between ‘awareness of consequences’ and car use as well as non-car use is small and not significant. However, this is based on a small number of studies (and observations). On the other hand, using a larger sample, Hoffmann et al (2017) find that the relationship between ‘awareness of consequences’ and car use, although not big, is negative and significant ($r_+ = 0.22^{***} ; k = 6 ; n = 2139$). This is same for ‘problem awareness’ effect on car use ($r_+ = -0.17^{***} ; k = 6 ; n = 5545$).

Moral and environmental norms are important change variables. Misunderstanding the TPB’s reasoned action assumption (Fishbein and Ajzen 2011) to mean that in this framework people are assumed to be rational utility-maximizers (Bamberg and Schmidt 1998), investigators have criticized the theory for underestimating the impact that moral beliefs and norms may have on people’s travel-mode choices. To remedy this situation, researchers have distinguished between subjective and moral norms (e.g. Parker et al 1996) and have assumed that, in the context of climate change, moral norms may be an additional predictor of a person’s intention to use more environmentally friendly modes of transportation. For instance, Abrahamse et al (2009) find that the TPB constructs (such as intentions and PBC) were more powerful than moral norms in explaining current car use for commuting but that moral consideration were more powerful predictors than the TPB constructs for intentions to reduce car use in the future. In their meta-analysis, Hoffmann et al (2017) report a pooled correlation of $r_+ = -0.35$ between perceived personal obligation of not driving (moral norm) and self-reported driving. For the same association, the other two meta-reviews report a pooled correlation of $r_+ = -0.41$, and $r_+ = -0.26$, respectively (Gardner and Abraham 2008, Lanzini and Khan 2017). Based on these results there is a growing consensus within the research community to view moral norms as an additional travel-mode-choice predictor, especially of the decision to use more environmentally friendly travel modes.

Other than personal moral norms, several other personality-relevant factors are also identified in the reviews, these include; environmental values, altruistic value orientation (AVO), and valuation of different travel concerns. For instance, Altruistic value orientation (AVO) shows medium-sized negative association
with (self-reported) car use \( r_+ = -0.31^{***}; k = 3; n = 184 \). (Hoffmann et al 2017). Overall, while these factors show small effects on car use, the evidence base for them is limited as most studies rely on small convenience samples.

4.1.1.2. Habit formation
Habits are an especially important predictor of travel mode choice and go beyond models of rational choice. It has also been argued that the TBP does not adequately account for behaviours that may be
regulated by automatic processes (Triandis 1977; but see Ajzen and Dasgupta 2015). For instance, when behaviours are practised in stable environments over time, they can be automatically initiated by environmental prompts with little or no conscious deliberation (Strack and Deutsch 2004). Thus, since daily travel tends to occur in stable contexts, the transport mode choice may over time become less of a conscious choice and more of a habitual response executed with little reflection (Gärling and Axhausen 2003).

However, the use of past behaviour frequency as an indicator of habit strength is problematic (Fishbein and Ajzen 2011). Thus, there is a growing consensus that a realistic model of travel-mode choice should also include an independent habit measure. For this reason, in their meta-analysis Hoffmann et al. (2017) include a summary of six studies using an independent measure of habit strength (Verplanken and Orbell 2003) for predicting a person’s travel-mode choice. They find a pooled correlation of $r = 0.47$ between the habit measure and travel mode used. Gardner and Abraham (2008) report a pooled correlation of $r_+ = 0.50$, and Lanzini and Khan (2017) of $r_+ = 0.42$. While independent habit measure addresses some of the issues related to habit as a psychological construct, other relatively new areas of research explore different ways. Two prominent approaches are covered in our review studies.

First, the studies looking at the impacts of involuntary workplace location on travel mode choice (Zarabi and Lord 2019). This approach can be useful in exploring the causal relationship between habit formation and travel mode choice. This research area is motivated by ‘habit discontinuity hypothesis’ (Verplanken et al. 2008), which posits that big changes in context offer an opportunity to move away from habitual decision-making to more deliberately considered decision-making. As a result, alternate travel behaviours are more likely to be considered and adopted under the guise of these large changes in choice contexts.

Second, the studies conducted in the tradition of mobility biographies, which look at the impact of key life events on travel behaviour (Müggenburg et al. 2015). They identify three key life events, where ample research exist: (i) household changes (formation, childbirth), (ii) labour market entry, and (iii) residential relocation. In the first two cases, the key life events are accompanied by greater reliance on the car. The third key event is often thought as an entry point to break old habits and establish new ones (often for instance by giving free public transport tickets for a limited time period).

### 4.1.1.3. Socio-demographic factors

Socio-demographic factors affect travel behaviour and travel mode choice, but these factors remain largely ignored in meta-analyses, and the overall evidence base is weak.

Car use differs between socio-demographic segments. Although women travel more frequently than men, the total distance of travelling is lower for women (Rosenbloom 2004) (Veterník and Gogola 2017). Besides, women are less likely to use cars (Best and Lanzendorf 2005). While this relationship is moderated by different factors such as employment status and household characteristics, it holds even after controlling for these factors (Rosenbloom 2004). Income and employment status are also often associated with car use. Typically, people with higher income are able to spend higher amounts on their transportation needs, translating into higher car ownership and use of car.

Similarly, for biking, there is some evidence that being young and a man increases the likelihood of bicycling (Muñoz et al. 2016). There is ambiguous evidence for the impact of higher income and education level on bicycle usage. In the literature review of bicycle use, 6 studies show a positive association with income, 5 studies show a negative association,
while a majority of studies \((k = 13)\) finds no association (Muñoz et al 2016). The impact of income level on the use of low-carbon travel modes, especially biking, may be mediated by car ownership (Muñoz et al 2016). A similar picture emerges for education level, where 5 studies show a positive association, 2 studies show a negative association, while 6 studies find no association (Muñoz et al 2016).

4.1.2. Social level factors
Social level factors are less well studied compared to psychological and built environment factors. Most of the literature focuses on social norms in the context of the theory of planned behaviour (TPB). However, recently there has been growth in the literature related to social factors with more focused and diverse approaches. Figure 5 summarizes the evidence for most important social-level factors, including the assessment of relationship strength and confidence scale rating.

| Symbol, \(r, r^+\) | Measure | Description |
|---------------------|---------|-------------|
| Correlation coefficient | \(r\) and \(r^+\) | A correlation coefficient is a statistical measure to indicate the strength of association between two variables. We classify \(r\) values on a scale of 1–5 with corresponding values \((r \leq 0.1, 0.1 < r \leq 0.2, 0.2 < r \leq 0.3, 0.3 < r \leq 0.5\) and \(r > 0.5\) are to be considered very weak, weak, medium, strong and very strong in magnitude). Common variations: Pearson’s correlation coefficient, Spearman’s rank correlation coefficient, averaged pooled correlation coefficient \((r^+)\) (for meta-analysis) |
| Regression coefficient | \(c\) | Regression coefficient describes the relationship between the dependent variable and the independent variable. We keep the original review/study description of the effect size wherever possible. Common variations: Logistic regression models, Probit regression models, Discrete Choice models |
| Elasticity | \(e\) | Elasticity is the ratio of the proportional change in one variable associated with the proportional change in another variable. We keep the original review/study description of the effect size wherever possible. Common variations: Elasticity estimates, weighted average elasticities (from reviews) |
| Mode share or mode shift | \(m, M\) | A modal share or modal split \((m)\) is used to represent the share of specific transport mode in comparison to all other transport modes. Mode shift \((M)\) represents the shift away from one travel mode to another mode. We keep the original review/study description of the effect size as much as possible. Common variations: increase/decrease in mode use, percentage modal shift, modal shift from cars to alternatives |
| For meta-analysis studies, we use the notation ‘\(k\)’ to the number of original studies and ‘\(n\)’ as the total number of observations. For quantitative studies ‘\(n\)’ refers to the total number of observations and \(N\) for the total number of individuals (only if reported separately). |

The local social environment matters for mode choice indicating the influence of spatial influence effect. For aggregate choices over pre-defined spatial configurations, the choice of transport mode tends to be influenced by the behaviour of others who live in the same residential area (Dugundji and Walker 2005). Controlling for endogeneity\(^1\) in discrete choice models, the parameter on the spatial influence effect drops \((c = 1.53, n = 2888)\) (Walker et al 2011). Students who live in neighbourhoods dominated by bicycle users, are less likely to drive \((c_{pt} = -2.14^{**}; n = 483)\) (Pike 2014). However, greater public transport or driving by others in the same neighbourhood has no significant impact on driving \((c_{dp} = -0.79; c_d = -0.56; n = 483)\). In the case of public transport use, average spatial network effect for transit use on transport mode choice is positive and significant for transit users in New York \((c_{pt} = 1.813^{**}; n = 1652)\) (Goetzke 2008). Additionally, a significantly negative spatial network effect exists between frequency of bike users, and the individual public transit use \((c_b = -1.99^{**}; n = 483)\) (Pike 2014).

Travel mode commonly used by people in one’s social networks is an influential predictor of own mode choice, this is often referred to as social

\(^1\)Endogeneity problem arises when there is a correlation between the relevant (explanatory) independent variable and the error term in the regression model. In the context of social influence effect, it implies that the same observed and unobserved attributes may influence both the individual and everyone in her peer group, making the estimated social influence effect biased.
influence effect. The probability of choosing a mode increases with the share of one’s social group that selects that mode (Walker et al 2011). Here again, the issue of endogeneity looms large. The parameter on the social influence effect drops in the discrete choice models controlling for endogeneity (c = 1.75∗∗∗; n = 2888) (Walker et al 2011). Concerning specific travel modes and social network effect, the presence of bike-users among individual’s social network is significantly correlated with lower car use (c_b = −2.40∗∗; n = 483) (Pike 2014). However, this not true for car (c_d = 1.70; n = 483) or bus users (c_pt = 0.38; n = 483) in one’s social network members and own car-use. The presence of bus-users in one’s social network is positively associated with higher bus usage by the individual herself (c_pt = 3.66∗∗∗; n = 483). Lastly, based on an instrumental variables approach, greater propensity to biking is related to the proportion of social network members that also bike (c_b = 0.978∗∗∗; n = 388) (Pike and Lubell 2016).

While these studies look at overall social network effect there is relatively little work on the specific mechanisms. Based on earlier work, we classify two different types of social influence effects. (i) Indirect effect, where a social network effect is primarily due to social or observational learning from one’s social group (community and social class), and (ii) direct effect (social network effect, peer pressure), where a social network effect is due to the explicit impact of others via., negative or positive feedback from one’s social group (e.g. relatives, friends, acquaintances, colleagues, etc.).

Both indirect and direct social network effects are relevant for mode choice, but the evidence base is sparse. Mimicking others in one’s socio-economic group has a stronger behavioural influence than similar underlying preferences exhibited by those in the same socio-economic group (Walker et al 2011). Another study shows that those who have frequently observed others owning a bicycle tend to be more positively inclined to have a bicycle than those who have less frequently observed bike ownership (Maness and Cirillo 2016). For more direct forms of social influence, Sherwin et al (2014) document that a significant number of the new regular bicyclists received encouragement (positive feedback) from colleagues, while others mentioned social disapproval (negative feedback) for using car especially from their friends.

4.1.2.2. Social norms

Our search yielded three meta-analyses where social norms are the focal point. In all three of these studies, social norms are studied in the context of TPB. Descriptive norms (perception of others’ mode choice) show a low-medium size relationship with travel mode choice. First, with respect to car use and perceptions about other people’s car use behaviour (car use descriptive norm); there is substantial disagreement between the three studies. Hoffmann et al (2017) find small negative relationship, however this effect is not significant across studies (r_p = −0.07, k = 3, n = 532). Gardner and Abraham (2008) report medium-sized positive relationship (r_p = 0.36∗∗, k = 2, n = 993), similar result is obtained by Lanzini and Khan (2017) (r_p = 0.255∗, k = 6, n = 2199). Furthermore, Lanzini and Khan (2017) find medium-sized positive relationship between self-reported intention of car use and perceptions about other people’s car use behaviour (r_p = 0.27∗∗, k = 7; n = 2706). Relatedly, Lanzini and Khan (2017) also find similar effect in the case of non-car use descriptive norm and non-car use (r_p = 0.214∗∗, k = 4) as well self-reported intention of non-car use.

For subjective norms, the evidence base does not yield unambiguous answers. However, best estimates suggest a small to medium effect size between subjective norms and travel mode choice. More specifically, (Hoffmann et al 2017) report a small to medium-sized positive association between car use and car-use subjective norms (k = 6; n = 1455; r_p = 0.20∗). Effect sizes varied considerably across studies (range from r = 0.03 to r = 0.52) with half of the studies observing non-significant associations. Similarly, (Gardner and Abraham 2008) report a small highly unreliable negative effect for car use subjective norm (r_p = −0.07, k = 2, n = 555). However, based on a larger number of studies, (Lanzini and Khan 2017), observe a medium-sized positive relationship between self-reported car use and subjective norm about car use behaviour (r_p = 0.23∗∗∗, k = 10, n = 2199). Furthermore, they also find stronger positive relationship between self-reported intention
of car use and subjective norm about car use behaviour ($r = 0.42^{***}$, $k = 7$, $n = 2906$).

The research on specific low-carbon transport modes and subjective norms is limited. Rather, the meta-analysis in our database provides results on the general category of non-car alternatives. For instance, (Hoffmann et al 2017) report that non-car-use is positively associated with stronger subjective norms towards not driving, though the effect is small to medium and heterogeneous ($r = 0.28^{**}$, $k = 6$).

Stronger effects of subjective norm on non-car use are reported in Lanzini and Khan (2017), both for self-reported non-car use ($r = 0.23^{***}$, $k = 12$, $n = 12737$) as well as self-reported intention of non-car use ($r = 0.41^{***}$, $k = 20$, $n = 16770$).

4.1.2.3. Social signalling and social identity perspective

Social signalling theory implies that a significant portion of individual mode choices can be explained by their value in terms of signalling certain values and/or social status (in addition to the utility gained from the choice). The evidence for social signalling and status is scattered across different domains and often requires interpretation. For instance, there is some qualitative evidence that the perception of who else is bicycling is more important than the perception that bicycling is common or frequent among community members (Handy et al 2010). If biking is perceived to be associated with higher-status individuals, then the likelihood of others being influenced is greater. This point towards the importance of perceived social status and the signal it sends the person engaging in the activity. Meanwhile, the social comparison variable shows a small positive effect ($r = 0.16^{*}$, $k = 6$, $n = 1247$) meaning that people who compare their actions with others’ and try to exceed others are also more likely to use the car (Hoffmann et al 2017). Concerning social identity effects, most of the studies rely on Theory of Planned behaviour as their theoretical basis, and find a very small, negative association between car use and anti-car identity measures ($r = -0.08^{*}$, $k = 11$, $n = 1609$), while a very small positive association is observed between car use and pro-car identities ($r = 0.05^{*}$, $k = 11$, $n = 4229$) (Hoffmann et al 2017).

4.1.2.4. Social practices and travel behaviour

So far, social level factors considered in our analysis rely on psychological theories and therefore tend to focus on individuals as a unit of analysis. Sociological literature and especially social practice theory, on the other hand, emphasize the primacy of ‘social practices’ as the key unit of analysis.

Cairns et al (2014) review the growing body of social practices’ literature on travel behaviour. Although empirical estimates are hard to come by, broadly speaking, three main insights arise from this literature. First, over time car has become associated with a unique set of values and meanings (such as concepts of freedom, moral commitment to family and care for others) (Sheller 2004), and other travel modes will need to tap into those values and meanings to achieve modal shift. Secondly, the meanings and symbols associated with cars are a result of complex interplay between individual and social values (Wollen and Kerr 2002). Car is construed as a cultural object, embedded in self-created social identity. Other travel modes which do not offer such possibilities are less likely to have the same allure as the car. Lastly, the ‘diversity of meanings and values attached to cars results from temporal and cultural specificity’ (Gartman 2004). Therefore, different groups form different norms around these meanings and values.

4.1.3. Infrastructure level factors

We divide individual level factors in two major subcategories; built environment factors and transport system factors. Figure 6 summarizes the evidence for most important infrastructure level factors, including the assessment of relationship strength and confidence scale rating.

4.1.3.1. Built environment

The search query yielded 16 reviews that investigate the role of the built environment in modal choice and travel demand.

Land use modifies travel prices both by distance and travel speed (Boarnet 2011). Reduced form estimates that regress travel behaviour to land-use determinants is the dominant methodology employed in this literature (Ewing and Cervero 2010); however such models are unable to reflect the endogenous role of land use planning, even though it is well understood that the interaction between travel and land use is bidirectional (Wegener and Fuerst 2004). Residential self-selection denotes that people chose their residence according to modal choice availability. The causal role of land use on travel behaviour may be attenuated but not negated by residential self-selection (Boarnet 2011; Cao et al 2009). However, elasticities are higher with self-selection controlled for; this suggests that there is latent demand for transit/bike oriented communities and that elasticities that do not control for self-selection underestimate the role of the built environment (Chatman 2009, Ewing and Cervero 2010). A review of residential self-selection confirmed the relevance of self-selection, highlighting that perceived characteristics rather than objectively measured characteristics were predictive; attitudes matter (Bohte et al 2009). The role of habits was not investigated in empirical studies on the built environment, begging for further investigation.

Neighborhood characteristics, such as walkability scores, parks, safety, aesthetics, and social environment are commonly related to active transport,
especially walking. Yet, most studies are purely observation-al and cross-sectional, thus remaining ignorant on the causal role of the built environment; instead social characteristics of inhabitants might explain the difference in active transport. A systematic review screened 3324 studies, finding 23 studies that investigated the influence of the built environment on active mobility longitudinally, specifically by observed behaviour before and after relocation between neighbourhoods with different characteristics (Ding et al. 2018). Retrospective studies show unambiguously that built environment characteristics shape active mobility patterns and intensity, while prospective studies show a weaker relationship. A key study performed a meta-regression relating land-use and socio-demographic variables on travel behaviour. It found a strong impact of accessibility, as the single most important land use metric, on travel behaviour (Gim 2013).

There is less clear evidence of how the preferences of inhabitants shape land-use planning. It is possible that cities planned low-density developments despite people’s preference for more compact cities (Levine 2010). It may simply be that cities plan similar to what is already there and that citizens accept this rationale, as they are used to it, and as others see this as a sensible choice to (Boarnet 2011). The question of the malleability of preferences in mode choice looms large but has hardly been studied. Meta-analytic results reveal that vehicles miles travelled (VMT) only marginally reduces with population density \( (e = -0.04, k = 9) \) and land-use diversity \( (e = -0.09, k = 10) \), more with street design (street connectivity: \( e = -0.12, k = 6 \)), and most with destination accessibility \( (e = -0.20, k = 5) \) (Ewing and Cervero 2010). Together, these urban form parameters may change VMT by about–0.25 (Boarnet 2011). Walkability improves most with intersection density \( (e = 0.39, k = 7) \) and job-housing balance \( (e = 0.19, k = 4) \); transit with street connectivity/4-way-intersections \( (e = 0.29, k = 5) \) and distance to transit stop \( (e = 0.29, k = 3) \) (Ewing and Cervero 2010).

Modelling studies suggest that increases in population density only produce a small reduction in VMT (about 0.5–1.7%). However, combining densification with improved transit access and road charging can increase this value to 25% over the time horizon of 40 years (Rodier 2009), in accordance with other modelling studies that investigate the confluence of push (pricing), pull (transit improvements), and land use (Creutzig and He 2009, Creutzig, Mühlhoff, and Römer 2012).

4.1.3.2. Transport system infrastructure

Across different categories, we find 15–20 major studies where substantial portions are devoted to the transport-system factors. As explained earlier, we divide the transport system factors into three main sub-categories.

First, concerning transport infrastructure factors, especially the provision of hard infrastructure, added capacity in the form of new highways increases VMT (Kitamura 2009). However, the impact on induced traffic, residential choice and car ownership remain less clear. There are several caveats which come with these findings including the shortcoming in methodology and data. More recent studies have come to the opposite conclusion (for instance, Duranton and Turner 2011).

In terms of low-carbon transport modes, provision of travel-mode specific and dedicated hard infrastructure is vitally important. For public transport, there is a clear indication that the provision of new PT infrastructure can lead to a shift away from cars to public transport. An international review of public transport report that new infrastructure such as BRT, LRT and rail transit systems can achieve up to 40% mode shift away from car traffic to public transport systems (Ingvarsdson and Nielsen 2018a). However, given the diversity of contexts and the infrastructure (such as type of infrastructure, length, etc) there is relatively high variance whether new infrastructure attracts previous car users or not (average mode shift estimates range from 5%–40% for new PT infrastructure in different cities). Overall, to achieve notable impacts on car traffic, attractive high-capacity systems (such as LRT) seem more effective (Ingvarsdson and Nielsen 2018a). There is a consensus in the literature that separated bicycle infrastructure, especially bike lanes and bike paths, increase bicycle usage. Indeed, a supportive network of different types of infrastructure appears necessary to attract new people to bicycling (Buehler and Dill 2016). According to Nuworsoo and Cooper (2013) cyclists associate 1 min of stress in mixed traffic with roughly 4 min of stress in a bike lane. Lastly, the literature shows a positive impact of infrastructure such as pavements on walking among adults (Bauman and Bull 2007). Some studies argue that while infrastructure is necessary for the promotion of walking, it is not sufficient and the proximity of activities to areas linked by such infrastructure can lead to a greater number of walking trips (Nuworsoo and Cooper 2013).

Factors related to transport system characteristics are consistently associated with a medium-sized effect size on travel mode choice. For public transport, system characteristics can be divided into two main aspects, coverage and connectivity of public transport systems. Based on a meta-analysis of 48 European metropolitan areas, Ingvarsdson and Nielsen (2018b) find that transport system coverage (rail, metro length in km/km²) shows high correlation with the total number of public transport trips per capita per year \(( \kappa_{\text{metro}} = 79.4^{* * *}; \kappa_{\text{sub}} = 85.7^{* * *}; k = 48 \)). This is especially true for metro coverage.
However, at the same time, most indicators of transport system coverage are linked with higher density, so it is difficult to parse out the role of PT coverage separately from the urban density. In terms of connectivity, they find that PT system connectivity as measured by two separate indicators, the cyclomatic number\(^2\) and the number of transfer stations, is linked with higher ridership \((C_{\text{network}} = 56.64^{+*}; k = 48)\). Focusing on bicycle infrastructure characteristics, the literature is not as extensive on bicycle infrastructure characteristics as compared to the literature on Public transit. However, there are some indications that bike infrastructure characteristics are important in much the same. For instance, bike lanes tend to produce a more positive feeling among users as compared to bike paths (Nuworsoo and Cooper 2013). However, this may be due to the limited availability of bike paths and the fact that they tend to be disconnected from each other. Furthermore, in the context of a public bike system in Ireland, connectivity to other public transport modes is a crucial factor in increased use of these bike systems (McBain and Caulfield 2018).

Last major sub-category of the transport system, quality of transport system, tends to produce only a marginal impact on travel mode choice. The literature on these factors focuses more on public transit, although walking and biking infrastructure qualities also appear in some restricted cases. Concerning public transit services, De Gruyter et al (2019) conduct a meta-analysis of customer amenity values in six countries (Australia, India, New Zealand, Norway, Sweden, and United Kingdom). They identify 556 separate customer amenity values and collapse them in 5 major categories (facilities, information, security, environment, condition). Overall, the meta-analysis indicates that these amenities have a relatively low impact on transit ridership. In travel time comparative terms, improvements in these aspects are very rarely valued higher than the equivalent of 1 mins reduction in in-vehicle travel time. In the context of bus networks, improvements associated with ‘soft’ variables are not likely to increase patronage by more than a few percent (Currie and Wallis 2008) \((m\) ranges from 2%–5% for the most effective measures). More concrete service attributes (such as speed, reliability, frequency) can increase ridership numbers substantially (Redman et al 2013) \((m\) ranges between \(\sim 25\%\) for speed, 10%–40% for reliability, and 20%–80% for frequency improvements).

Redman et al (2013) argue that hard infrastructure factors encourage car users to switch to PT, whereas the quality attributes determine the duration of this effect. Loyalty to PT use may be determined by soft transport factors. There is some evidence to suggests that regular transport users value these soft factors more that (non-regular) users (De Gruyter et al 2019). However, in many cases, it is difficult to measure whether the effect is produced by a change in quality attributes or by the provision of the infrastructure itself.

4.1.3.3. Weather/natural environment

While, this is not the focus, there are several studies, which mention the impact of natural environment and weather on travel mode choice. This is especially true for biking and walking. In particular, the slope of the land and rainfall are mentioned as major deterrents to walking and biking. Böcker et al (2013) conduct a meta-review of studies related to weather conditions on active travel. They find that warm and dry weather conditions influence the use of active transport modes positively. Rain, snow, windy, overly cold or hot weather can have the opposite effect. Furthermore, subjective weather interpretations (speed, effort, safety or aesthetics during trips) tend to have higher explanatory value for behavioural responses than objectively measured weather conditions.

4.1.3.4. Price and time elasticities

Most of the reviews on cost (price, time) elasticity of different transport modes are based on studies from the UK. For price elasticities, (Hensher 2008) conduct a meta-review of studies from a wide set of countries, and find that the mean elasticity estimate for fares is close to \(-0.395 \pm 0.274\) which is similar to the estimates reported in earlier reviews. In a similar vein, meta-analysis for the UK finds that the long-run car kilometre elasticity ranges between \(-0.20\) to \(-0.35\) depending on the length of the trip (Wardman 2014). Similarly, rail price elasticity ranges from \(-0.18\) to \(-0.31\) in short term and \(-0.70\) to \(-1.19\) in the long-run, whereas bus elasticities can be taken to be \(-0.4\) in the short term, and in the range of \(-0.7\) to \(-0.9\) in the long term. Importantly, both Wardman (2014) and Hensher (2008) report that the commuting and peak elasticities tend to be similar and, lower than the leisure and off-peak elasticities.

Secondly, for time-based elasticity values, in general, the meta-reviews find that in-vehicle time elasticities are on average greater than the headway elasticities (transit service frequency). Travel time elasticity related to car use varies considerably between the frequency of trips and vehicles miles travelled (VMT) in the long and short term evaluations. The representative value for long term (trip frequency) time elasticities is between \(-0.26\) for EU data (De Jong and Gunn 2001) and \(-0.29\) for UK data (Wardman 2012). Interestingly, long-term VMT time elasticity is around 2–3 times larger than the trip frequency-time elasticity, indicating that the long-term response to time variations is concentrated in the distance travelled by car.
(De Jong and Gunn 2001, Wardman 2012). Representative in-vehicle time elasticity for local bus (rail) range between −0.16 to −0.26 in the short-run and −0.4 to −0.6 in the long-run. Headway elasticities range from −0.07 to −0.12 for bus and train trips in the short-run, and −0.24 to −0.42 in the long-run (Wardman 2012). It’s important to note that these elasticity values vary between regular and non-regular users. Commuters tend to be less sensitive to fares and in-vehicle time, but more sensitive to headways, than non-commuters (Hensher 2008).

Lastly, in terms of inter-modal cross elasticities, elasticity values differ between price and time-based attributes. Representative fuel-price cross-elasticity for the shift away from the car to alternative transport modes show rather low values, ranging between 0.03 to 0.1 in the long-term (De Jong and Gunn 2001, Wardman et al 2018). The cross-elasticities of both bus and rail for the car are relatively large, long-term cross-elasticity values range from 0.2 to 0.33 for personal travel (Wardman et al 2018). Cross-elasticities to (in-vehicle) time-based attributes tend to exceed those for price-based attributes. This is especially true for public transport options, but also car elasticities. Overall, the findings from these reviews suggest that the role of improving public transit costs plays only a relatively minimal role in terms of reducing car demand. However, increasing in-vehicle time for cars can deliver relatively higher gains.

4.1.4. Information

The evidence base for the effectiveness of different forms of information on the adoption of low-carbon transport mode adoption is limited but growing. This is especially true within the context of the rise of information and communication technologies (ICTs) in the transportation sector. Andersson et al (2018) review the literature on the underlying theoretical and practical issues surrounding ICTs and behavioural change in urban transportation.

The accuracy of real-time travel information, feedback and self-monitoring, social networks, rewards and privacy emerge as key issues involving information effectiveness (van Essen et al 2016). Concerning public transport, communication with final users is the crucial element for sustained impact (Mangiaracina et al 2017). Up-to-date and easy-to-access information is particularly important for public transport use (Grotenhuis et al 2007). For instance, the provision of bus tracker service led to small, but significant increase in bus ridership (Tang and Thakuria 2012). The framing of information can impact the effects of information provision on travel mode choice (van Essen et al 2016). As discussed in the section on descriptive norms, social information, information about the choices of others, could lead towards desired behaviour (Sumitioyo and Matsumoto 2009). Travel information can also be provided using loss framing in which the presentation of choice alternatives highlights their negative individual and social impacts (Avineri 2009), enabling decision-makers to maintain eco-friendly choices.

The impact of information relies on who and how information is accessed. Results from transit-based smart parking implemented in San Francisco, indicates that only around one-third of respondents were aware of the existence of the information, and less than one-third of the people who saw the information considered it to make the travel mode choice decision (Rodier and Shaheen 2010). More broadly, three groups are specifically inclined to use ICT services related to travel behaviour: ‘the innovative technology-loving multioptionals’, ‘flexible car-lovers’ and ‘the ecological bicycle and Public Transit-lovers’ (Hinkeldein et al 2015).

4.2. Conditional and interaction effects

The information on conditional and interaction effects is missing from most of the studies considered for this review. This information may be more readily available in original studies, rather than literature reviews. However, given the interest in practical and theoretical applicability of results from reviews, it is imperative to consider these additional effects that are likely to determine how well estimated/reported direct effects translate to other contexts as well as the priority areas for intervention. Below we summarize the key findings from our review of the literature and classify them according to our framework definitions. Figure 7 summarizes the most important findings on conditional effects.

For conditional effects, we are interested in three main categories:

i. Individual effects conditional on infrastructure factors [(a|S) and (a|E)]

ii. Social effects conditional on infrastructure or individual factors [(b|I) and (b|E)]

iii. Infrastructure effects conditional on individual or social factors [(c|S) and (c|I)]

First, conditional individual effects, (such as demographics | built environment; PBC or psychological factors | BE; psychological factors | social norms) are interesting and potentially ripe for data collection. However, there is no systematic information available on these in our evidence base. Secondly, concerning conditional social effects, we find some interesting examples. For instance, Pike and Lubell (2016) find that social influence effect is most important when the external commute characteristics entail relatively equal travel costs for different modes. Similarly, they also find that social influence effect is dependent on travel distance. Given higher travel distances, social influence decreases substantially. Distance explains 35% of the variation in ego bike share. Similarly, social network effects are dependent on trip types.
Social network effect increases the probability of cycling for shopping and recreational trip purposes, but not for school, work or errands (Pike and Lubell 2016).

Adkins et al (2017) conclude that disadvantaged social groups are less likely to benefit from improvements in built environment factors related to walkability. According to their estimates, the built environment effect on weekly transport walking is 20.6 min or 130% more in supportive versus unsupportive built environments for disadvantaged groups. Whereas, similar differences in the built environment are associated with 410% more walking for advantaged groups. Muñoz et al (2016) argue that in areas with a more ingrained bicycle culture, the most common barriers are related to practical issues (distance, bicycle availability, weather, out-of-work commitments, sweating and effort; safety).

Concerning transport system effects conditional on individual factors, elasticity values for car travel than females, which means that price changes are less likely to reduce car trips by men as compared to car trips by women. Similarly, travellers with high incomes tend to have higher elasticity values. Lastly, elasticity values from Australia and the US differ from those obtained in other places (mostly EU countries) (Hensher 2008). Price effects depend strongly on infrastructure availability. In a highly detailed scenario of carbon pricing of Paris urban transport, carbon prices doubled their effectiveness (price elasticity), compared with a counterfactual scenario where public transit infrastructure was absent (Avner et al 2014).

Lastly, for the interaction effects, it is pertinent to mention that we are interested in only the aspects of interactions which are important for travel mode choice. Here, the literature offers only very limited context. Figure 8 summarizes the key findings.

Design of the built environment and control beliefs are closely related, but quantitative studies are mostly lacking. The perception of safety, especially among women, often depends on infrastructure factors. There is some evidence to indicate that good lighting has a positive role in reducing women’s fear. Similarly, good visibility and natural surveillance opportunities of transit stops and stations from surrounding establishments are other positive features (Cozens and Hillier 2012). Whereas, corridors and ramps leading to the underground station; the presence of graffiti and litter at transit settings, the absence of visible staff, the inadequacy of travel information, long wait times and infrequent service contributed to feelings of insecurity (Loukaitou-Sideris 2014).

Preferences on infrastructures differ between demographic groups. For instance, based on a meta-analysis of the relevant literature, Aldred et al (2017) find that most studies report that women and older people express somewhat stronger preferences for segregation from motor vehicles as compared to men and young people in general. Similarly, there are differences in preferences such as business attitudes towards infrastructure (Dudley et al 2011), as well as infrastructure for different population subgroups such as, for senior citizens (Yen et al 2014, Laiu et al 2018), families with young adults (Mccarthy et al 2017) and people with cognitive impairments (Risser et al 2015).

5. Discussion: upcoming topics in transport mode choice literature

In this section, we discuss topics not covered in the first set of review papers, which are nonetheless important for travel mode choice, especially in determining future trends. This is based on a second round of reviews (20 additional review papers) that cover developments which have not yet accumulated a sufficient body of empirical evidence for systematic reviews. We present these topics in the form of a narrative review.

5.1. Shared mobility

Currently, four different models of shared mobility exist; peer-to-peer car rental services; car clubs; service providers that do not own cars but sign up car owners as drivers; on-demand services shared by passengers going in the same direction (Santos 2018).

Drivers of shared mobility services are largely based on monetary and time savings along with convenience (Shaheen et al 2011). Shared mobility services are typically more successful in densely populated urban areas where there is a critical mass of users, competing directly with public transit. Sharing space and social engagement have been reported as both positive and negative motivations for participation in car-pooling schemes. ’Social tie strength and generalized social trust have been found to influence car-pooling more than socio-demographic factors’ (Dickinson et al 2017).

So far, the positive impact of shared mobility on the usual forms of transport has been relatively minor, especially on reduction in car-use (Rayle et al 2014). Indeed, there is some indication that a significant share of shared mobility trips is replacing public transit usage (Le Vine et al 2014). For instance, in California, a large number of users suggested that they may have walked or biked if car-sharing was not a possibility (Circella et al 2016); and in Jakarta positive effects from modal shifts from private cars to motorcycle sharing were counterbalanced by other trips replacing public transit (Suatmadi et al 2019). Shared mobility tends to have a more unambiguous impact on vehicle ownership. The rate of vehicle ownership among members of urban car-sharing programmes tends to be lower (between 10% and 30% decrease by some estimates) (Standing et al 2019; Santos 2018).

Shared mobility may have increasing impact on reducing traffic congestion and car travel once the
network of users has grown from the current low mode share. However, this is countered by the suggestion that greater flexibility and affordability of shared mobility will result in more induced travel demand (Sun et al 2016). Overall, it is difficult to say which equilibrium is reached in the long run as currently shared mobility trips are mostly concentrated in relatively large cities (Standing et al 2019). If the pull factor of convenient shared mobility is complemented with push policies, such as pricing cars out of cities (Creutzig et al 2020), and by digital urban governance, shared mobility would likely translate into both improved accessibility and lower total GHG emissions (Creutzig et al 2019).

5.2. New mobility and ICT services

5.2.1. E-bikes
An electric bicycle also known as an e-bike or electrically-assisted bicycle—require pedalling, but the rider have the option to switch on battery-powered assistance (Cairns et al 2017). Studies show e-bike commuters make longer trips, especially when comparing e-bikes to conventional bike users (on average the difference is between 3–4 km) (Engelmoer 2012). The travel time of e-bike trips is comparable to other modes in urban areas. In many cases e-bikes fare better than other modes, resulting in reduced travel time (Drage and Pressl 2010; Cairns et al 2017). Most importantly, the proportion of e-bike trips that replace car use (mode shift), are reported to be between 40%–70% (Cairns et al 2017). Lastly, e-bike use and ownership may have a small, volatile impact on car and motorbike ownership rates (Wolf and Seebauer 2014).

5.2.2. ICTs and lifestyle changes
Other than the direct effects of ICTs, new ICT services can also have indirect effects on travel behavior via changes in lifestyle choices. Broadly, these changes can be described in three different categories.

Teleworking (Telecommuting): there is evidence that telecommuters and their household members travel less (de Graaff 2004), although the overall impact is less significant due to latent demand (Mokhtarian and Salomon 2002). Arguably, new ICT services can promote long-distance travel by creating opportunities for sustained interactions (Aguiléra et al 2012).

Teleshopping: conceptual and empirical studies in the field of ICT and transportation suggest that e-shopping may interact with travel behavior in four ways: substitution, complementarity, modification, and neutrality (Xinyu Cao 2009). The overall trend for shopping-related travel shows somewhat mixed results (Weltevreden and Rotem-Mindali 2009). The analysis for only e-shoppers also showed a minimal effect (Weltevreden and Rotem-Mindali 2009).

ICT effects on urban form: ICT can have two opposite effects on urban form and built environment factors: dispersion, and reinforcement of concentration (Cohen-Blankshtain and Rotem-Mindali 2016). However, urban changes require a long time span as the changes are mostly incremental and slow. Thus, identifying important expected urban changes requires a long-term perspective and has yet to be examined empirically, in a satisfying manner.

5.3. Transport behavior in Global South
A vast majority of the studies in our review of review are related to high-income countries. The lack of a greater focus on transport issues in low and middle-income countries coupled with limited information on conditional effects, means that generalizability and transferability of review findings are undermined. We can not say whether the relationships discussed in this review hold across contexts that are different than the ones discussed and analyzed in the underlying papers. Furthermore, this shortcoming belies a lack of strategic foresight. It is in these countries (especially middle-income ones), where transitions towards mostly individual motorized transport are happening. Counterfactual modal pathways are especially important in these countries and could be associated with low-cost investments, and high benefits for societies, climate change mitigation, and the environment enlarge (Schäfer 2005).

Here, we provide a brief narrative review of unique challenges and developments related to travel behaviour in low and middle income countries.3

Many cities in low-middle income countries have seen a dramatic shift away from walking and biking to motorized transport, especially two-wheelers (Zhenqi and Weichi 2017). For instance, walking share in Dehli and Chennai has fallen from around 40% in 2002 to around 20% in 2008, with most of the gains going to two-wheelers and cars (Leather et al 2011). The higher incidence of two-wheelers in low-middle income cities, although requiring less space than cars, however, is associated with other social and environmental problems (safety, pollution, emissions, and even congestion).

Cities in low and middle-income countries have a high spatial concentration of population and income. Furthermore, there is often inadequate supply of transport infrastructure combined with weak traffic management (Gwilliam 2003). So, even though the current share of car users is relatively low in low-to-middle income cities, congestion and other issues are often more severe as compared to high-income cities. Relatedly, the safety of travellers is a bigger issue in these cities. Accidents rates are higher for both pedestrians (bik users) as well as motorized transport users (cars and motorbikes) (Gwilliam 2003). Lastly,

3We thank one of the reviewers for their suggestion to discuss this issue in more detail and highlight this limitation more prominently.
the public transport system in low-middle income cities with notable exceptions, suffer from issues about service reliability and safety. This is compounded by the lack of financial and institutional capacity to run sophisticated, well-integrated public transit systems offering wide coverage (Gwilliam 2003). These weaknesses in public transit are reflected in people’s opinion on public transportation. For instance, in India, transport users rank safety as the most important criteria for encouraging the urban commuters to shift from private vehicles to public transport and followed by reliability, cost and comfort (Jain et al 2014).

Given these unique challenges, there have been many innovative solutions gaining traction among urban planners and administrators in global south cities. Chief among them is the rise of BRT systems that ease some of the financial and institutional constraints in public transit management. There has also been a greater focus on hybrid public transport systems that combine elements of both public and private transit and paratransit operators (Ferro et al 2013). Meanwhile, motorcycle taxis, e-bikes and new ride-sharing platforms are also well-suited to the needs of travel users in these cities (Ehebrecht et al 2018). Nonetheless, the dearth of reviews on issues specific to and set in low-middle income countries, suggests a critical gap in consolidated literature. This implies that not only the problems relevant to these countries are neglected but also that solutions arising from these countries are ignored, resulting in poor understanding and stalled progress on tackling transport related emissions.

6. Conclusion

Mode choice and resulting environmental impact of urban transport depend on individual beliefs and motivation, social effects, and the quality of the transport infrastructures. In this review of reviews, we synthesize insights on factors contributing to mode choice, and specifically mode shift from automobiles to environmentally friendly modes, drawing from psychological, sociological, and the built environment literature (figure 9 provides a summary of our key findings).

We find that all three dimensions unambiguously interfere with mode choice. Individuals are most motivated to shift modes, if they are well informed, if personal norms match low-carbon mode use, and, most importantly, if they perceive to have personal control over decisions (perceived behavioural control). Descriptive social norms, especially if supported by subjective norms, are highly influential to support mode shift. However, the overall margin of shift as induced by individual and social settings remains limited. Instead, the infrastructure factors (such as the transport system and built environment) explains considerable differences in mode choice. Especially, accessibility metrics, such as distance to jobs, and street connectivity, an important measure of pedestrian access, as well as dedicated bike infrastructures play a crucial role in enabling modal shift.

The infrastructure dimension also enters the individual perspective as part of perceived behavioural control. Only in built environments where choices can be safely made and resulting time costs remain limited, perceived behavioural control translates into an individual opportunity to modal shift. Prices play an important role in interacting with all other factors. For example, increased fuel taxes translate into about a factor of two higher modal shift if public transit infrastructures are available. Similarly, there is evidence that carbon pricing supports a shift in social norms towards environmentally friendly behaviour, resulting in a mutually supportive cycle—as far as not constrained by infrastructure.

Our review of reviews also highlights gaps in research. Most importantly, studies of interaction and non-linear effects between psychological, social and behavioural dimensions remain limited. Conditional effects across categories are also mostly missing in existing reviews. This is at least partially grounded in the challenge of controlling for all these dimensions, and to obtain reliable data. Nonetheless, in-depth studies on interaction and conditional effects would have a very high value. As an alternative, the transition towards low-carbon mode choice can be investigated in cities with a successful track record. This includes Copenhagen, Amsterdam and other Dutch cities, which moved to majority-cycling cities; Curitiba and Bogota, which moved to bus-rapid transit systems; Edmonton and Denver, which built light-rail into car-dominated cities; and Beijing and other Chinese cities, which implemented ambitious bike-sharing systems.

Our review of reviews also identifies specific factors that lack analysis. For example, social factors have been studied less extensively than other factors. This shows in almost complete lack of social signalling and cultural formulations in these review studies. Furthermore, current work on social factors is based on measures with limited construct validity. In some ways it mirrors the development in measuring habit formation, however, in the case of social influence and social norms, these problems remain unaddressed. Further development of these measures and relating them to more detailed measures of travel mode choice is an important area of future research.

Another area of improvement is the establishment of common evidence standards. Evidence is often problematic due to arcane empirical design, and biased and incomplete measurement. This is especially important for measuring the use of low-carbon transport modes. Often the measures reflect a broad array of transport choices, from regular use to actual frequency, which makes it hard to quantify the effects across different variable categories. We suggest that standardization of metrics and the development of
common frameworks would certainly support progress in synthesizing results across disciplines. In our review of reviews, we try to systematize evidence standards by applying the IPCC guidance note on confidence levels to the observed relationship. The results, in turn, provide a systematic guide of where research would be most valuable.

This review of reviews offers an entry point for interdisciplinary research on modal choice and specifically on the modal shift towards low-carbon modes. We hope, content-wise, that it serves as a useful starting point for in-depth analysis of low-carbon urban transport transitions, and epistemologically, that it contributes to fostering collaboration between communities.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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