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Striving for low-carbon lifestyles: An analysis of the mobility patterns of different urban household types with regard to emissions reductions in a real-world lab experiment in Berlin

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Max Juri Bäuerle

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- an analysis of the mobility patterns of different urban household types with regard to emissions reductions in a real-world lab experiment in Berlin

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Abstract

The transport sector has so far shown little success in reducing emissions. Demand-side solutions such as lifestyle and behavioural changes of individuals and private households entail extensive reduction potential that could greatly complement technological solutions in transport. Private households are therefore relevant actors through their transport demand and modal choice. Yet, challenges and opportunities for reducing emissions vary with the *household living situations* and individual preconditions for action. The *real-world lab experiment* KLIB pursued to support and motivate households that intended to reduce their *carbon footprint* during an one year real lab phase using a *carbon tracker* tool. Based on the KLIB mobility data, this study aims to enhance understanding on the extent of emissions reductions through voluntary changes in mobility behaviour. This implies to identify through which changes in modal choice and transport demand how much of emissions reductions were achieved and where obstacles and limits to voluntary efforts existed. A mixed-methods research design is adopted: transport sociologically grounded *type formation* groups the KLIB households along relevant household characteristics. Subsequent type-based statistical data analysis examines changes of the types' mobility patterns and associated emissions. The findings indicate that within everyday ground mobility voluntary behavioural changes like the shift to low-carbon modes can lead to considerable emissions reductions depending on the household living situation and particularly car equipment. Nevertheless, *car ownership* presents a strong *carbon lock-in* and barrier to emissions reductions. Contradictory results are provided by air travel, where emissions increase for almost all household types, offsetting or outbalancing ground mobility savings. It emerges that behavioural changes are context-specific and constrained by counteractive effects and obstacles, especially in holiday contexts and emissions-intensive air travel.

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1 Introduction

1.1 Context and problem definition

Mobility is a central part of our daily lives and a precondition for social participation by enabling everyday activities. At the same time, mobility and transport have become a source of daily discomfort due to congestion, traffic jams and air pollution in cities (Bongardt *et al.*, 2013). But above all, transport confronts us with great challenges in terms of climate change (IPCC, 2014, pp. 46 f., 88; Creutzig *et al.*, 2015).

The Sixth Assessment Report of the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) leaves no doubt that humanity is currently on track to reach the 1.5 °C global mean temperature increase compared to pre-industrial levels, probably as soon as the early 2030s (IPCC, 2021). Present global emissions reduction plans, based on existing policies and actions of all countries combined, are insufficient to meet the climate targets of the Paris Agreement and would lead to a global average temperature increase of 2.7 °C by 2100 (UNEP, 2021). Factoring in recent announcements for the 2030 targets at the 26th UN climate change conference in Glasgow, known as the Conference of the Parties 26 (COP26), the Climate Action Tracker consortium projects a temperature increase of 2.4 °C (CAT, 2021). In order to limit global warming to 1.5 °C in the long term, rapid and deep decarbonisation of all sectors and areas of society is required, in terms of production, activity and consumption. In terms of activity and consumption, private households are crucial actors through their lifestyle and consumption patterns (Akenji and Chen, 2016; Dubois *et al.*, 2019; IGES, Aalto University and D-mat Ltd., 2019; Vita *et al.*, 2019; Costa *et al.*, 2021). According to different studies, 60 to 72 % of global greenhouse gas (GHG) emissions are attributable to household consumption and lifestyles (Hertwich and Peters, 2009; Ivanova *et al.*, 2016). Mobility and transport are particularly emissions-intensive in the context of household consumption and activity (Ivanova *et al.*, 2016; IGES, Aalto University and Ltd., 2019), but constitute a distinct obstacle to climate protection far

beyond the individual household sphere¹, both at the national and international level (Creutzig *et al.*, 2015).

Transport is responsible for about 24 % of direct CO₂ emissions from fuel combustion worldwide, with road transport accounting for nearly three-quarters of that (IEA, 2020). Yet, apart from the last year's emissions slump due to the SARS-CoV-2 crisis (cf. ITF, 2021), the transport sector is showing little success in emissions reduction (Creutzig *et al.*, 2015; IEA, 2020). On the contrary, recent projections indicate that with current policies and growing demand, emissions are more likely to increase globally, up to 16 % by 2050 (ITF, 2021). In Germany, the transport sector contributed the least to climate protection compared to all other sectors. Emissions in 2019 were even 0.4 % above the 1990 reference level (UBA, 2021b, p. 73). Overall, transport was accountable for 165.5 Mt CO₂-eq or around 20 % of total GHG emissions in Germany for 2019 (total: 810 Mt CO₂-eq), ranking it the third largest emitting sector after the energy and industrial sectors² (UBA, 2021e, 2021h, p. 11). The main contributor within the transport sector is road transport with 158 Mt CO₂-eq in 2019, which equates to 95.5 % of total transport-related emissions (UBA, 2021b, pp. 213 f., 215 f.). If only passenger transport is considered, the *motorised private transport*³ (MPT) alone is responsible for 75 % of CO₂-eq emissions⁴ (Allekotte *et al.*, 2021; UBA, 2021b, pp. 214 ff.). The second major driver in passenger transport is international air travel departing from

¹ For methodological reasons of approach and delimitation of the topic, this study examines the problem of transport-related emissions primarily from the consumption-based perspective of households and individuals, in the knowledge that governments and companies such as car manufacturers and airlines are decisive actors and bear at least equal responsibility. This study is interested in the potential for emissions reductions by private households rather than in any form of responsibility transfer or finger-pointing.

² In the delimitation of sectors according to the German government's Climate Protection Plan 2050 (cf. BMU, 2016).

³ The *motorised private transport* (MPT) includes cars, motorised two-wheelers, trucks and other motorised vehicles (Nobis and Kuhnimhof, 2018, p. 131).

⁴ CO₂-equivalent (CO₂-eq) emissions is a measure of the Global Warming Potential (GWP) of a greenhouse gas (GHG) and represents the emitted amount of the reference substance CO₂, that would cause the same radiative forcing, over a given period of time (usually 100 years), as an emitted amount of a particular GHG or a mixture of GHGs (IPCC, 2014, pp. 121, 126; cf. 3.3.2).

Germany, which accounts for 19 % of CO₂-eq emissions (Allekotte *et al.*, 2021; UBA, 2021b, p. 161, 163).

Against this backdrop, it becomes clear that a transformation towards an ecologically sustainable transport system is needed, and concomitantly, a change towards a sustainable mobility demand. A corresponding change is thus only conceivable as a societal transformation, i.e. also as a cultural and social change process rather than just a technical one (Ruhrt, 2019, pp. 11, 25). In this context, the IPCC already highlighted in its Fifth Assessment Report, the influence of lifestyles, behaviour and culture on emissions and states high mitigation potential through lifestyle and behavioural changes, in particular if they complement technological and structural change, as is feasible in the transport sector (IPCC, 2014, pp. 29, 100). Seven years later, the third part of the IPCC's Sixth Assessment Report (officially still unpublished), recently leaked by Scientist Rebellion, points out that "*adoption of many technologies have progressed, but deployment rates, deployment patterns, and the global reach of technological change is currently insufficient to achieve climate and sustainability goals (high confidence)*" (IPCC (Scientist Rebellion leak-publication), 2021, p. 8). Furthermore, it states that demand-side options in the end-user sector have a global GHG emissions reduction potential of 50–80 % by 2050 with energy end-use technologies contributing most to mitigation in the transport, building and industry sector (IPCC (Scientist Rebellion leak-publication), 2021). Consequently, it is important to leverage the potential of demand-side actions related to lifestyle and behavioural changes as fast and cost-effective mitigation options (Creutzig *et al.*, 2016; Costa *et al.*, 2021). Low-carbon energy technologies are crucial to adequately reduce GHG emissions. However, demand-side actions, would distinctly enhance the emissions reduction potential and greatly complement technical solutions (Creutzig *et al.*, 2016, 2018; van Sluisveld *et al.*, 2016; Costa *et al.*, 2021). This is particularly the case in the transport sector, if technological and structural change enhances the options and opportunities of low-carbon mobility, which in turn influences changes in preferences and social norms that can induce behavioural change (IPCC, 2014, pp. 29, 100; Creutzig *et al.*, 2016, 2018; Javaid, Creutzig and Bamberg, 2020). Only the complementary interplay of rapid

behavioural changes and the adoption of low-carbon technologies, as well as the systemic transformation towards low-carbon infrastructures, is expected to achieve the necessary emissions reductions in time and keep the 1.5 °C target within reach (IPCC, 2014, pp. 94, 100; Rogelj *et al.*, 2018, pp. 97, 161; Creutzig *et al.*, 2016; Costa *et al.*, 2021).

For the quantification of the emissions reduction potential through lifestyle and behavioural changes of individuals and households, a *carbon footprint* approach to emissions accounting is reasonable. It holistically maps direct and indirect or embedded GHG emissions generated by activities or consumption of products throughout their entire life cycle (Peters and Hertwich, 2008; Wiedmann and Minx, 2008; IGES, Aalto University and Ltd., 2019). The correct allocation of emissions thus opens up decisive mitigation options in terms of lifestyle and behavioural changes at the individual or household level (Schächtele and Hertle, 2007; Peters and Hertwich, 2008). Based on current lifestyles and consumption patterns, the Institute for Global Environmental Strategies (IGES), Aalto University and D-mat Ltd. (2019) proposed *lifestyle carbon footprint* targets of 2.5 t CO₂-eq by 2030 and 0.7 t CO₂-eq by 2050 along emissions reduction scenarios consistent with the 1.5 °C target. Especially for developed countries such as Germany, large gaps were found between the current and the proposed target lifestyle footprints. They further identified a major need for carbon footprint reduction primarily in the field of mobility (as well as housing and nutrition): for developed countries it would require a sharp reduction of 72 % by 2030 and a reduction of 96 % by 2050 to be in line with 1.5 °C mobility lifestyles (IGES, Aalto University and Ltd., 2019). With a current average carbon footprint of about 11.2 t CO₂-eq per capita and year and around 2.1 t CO₂-eq (19 %) alone attributable to mobility, Germany is clearly far from that target (UBA and KlimAktiv, 2020d).

From a carbon footprint perspective of private households, MPT and air travel are the strongest drivers of emissions in mobility or passenger transport (Akenji and Chen, 2016; Ivanova *et al.*, 2018; IGES, Aalto University and D-mat Ltd., 2019; Dubois *et al.*, 2019). In Germany, the MPT is problematic due to its transport volume and *transport*

*performance*⁵ concerning its emissions intensity per *passenger-kilometre* (p-km) (Allekotte, *et al.*, 2020, pp. 122 f.; Allekotte *et al.*, 2021). But air travel is more emissions-intensive: additional *non-CO₂ effects*⁶ amplify the climate impact by a factor of 2–3 compared to pure CO₂ emissions (UBA, 2019; Allekotte *et al.*, 2020, p. 123; Lee *et al.*, 2021). In other words, air travel is the most emissions-intensive single activity when considering individual consumption and thus has a significant impact on the carbon footprint (Allekotte *et al.*, 2020, p. 123; Ivanova *et al.*, 2020; Gössling, 2021). Conversely, this implies that lifestyle and behavioural changes that involve refraining from a private car or reducing air travel and shifting to low-carbon modes of transport bear the greatest emissions reduction potential in the domain of household mobility (Akenji and Chen, 2016; Ivanova *et al.*, 2018; IGES, Aalto University and D-mat Ltd., 2019; Dubois *et al.*, 2019; Ivanova *et al.*, 2020).

Both mobility behaviour and carbon footprints, however, are largely influenced by the *household living situation* and its socio-demographic characteristics such as income, household size, gender, age structure, educational level and vehicle equipment (cf. Ornetzeder *et al.*, 2008; Minx *et al.*, 2013; Jones and Kammen, 2014; Ivanova *et al.*, 2016, 2017; Kleinhüchelkotten, Neitzke and Moser, 2016; Miehe *et al.*, 2016; Scheiner, 2016, pp. 691 ff.). Correspondingly, the potentials and opportunities of households to reduce their mobility carbon footprint vary with the households' living situation and the individual preconditions for action, and not least with the existing transport infrastructural and political framework conditions (Creutzig *et al.*, 2016; Ivanova *et al.*, 2018; Dubois *et al.*, 2019). In fact, there are clear barriers to behavioural change towards low-carbon mobility at the infrastructural, technological, institutional and

⁵ In passenger transport, the distance travelled with means of transport is expressed in the *transport performance*. The transport performance is the product of the kilometres travelled and the number of persons transported (unit: *passenger-kilometres* = p-km) (UBA, 2012, p. 66; Nobis and Kuhnimhof, 2018, p. 132; cf. section 3.3.2).

⁶ The additional radiative forcing (climate impact in relation to the GWP) of aviation emissions such as water vapour, particles, nitrogen oxides and their chain effects is referred to as *non-CO₂ effects*. Since the emissions are introduced into higher atmospheric layers, they amplify the climate impact of air travel emissions by a factor of 2–3 compared to the pure CO₂ emissions (Lee *et al.*, 2021; UBA, 2021b, pp. 207 f.; cf. section 2.1.2).

behavioural levels: path dependencies in the form of existing infrastructure (e.g. car-centred road and urban infrastructure), technology (e.g. dominance of internal combustion engine vehicles or MPT), institutions and policies (e.g. environmentally harmful subsidies in the transport sector) as well as the behaviour of individuals (e.g. existing habits and routines related to car use) and societal collectives (e.g. social norms of carbon-intensive transport and travel behaviour) constitute so-called *carbon lock-ins*⁷ in carbon-intensive emissions pathways, which are distinct obstacles to low-carbon mobility (Seto *et al.*, 2016; Ivanova *et al.*, 2018). Individually and in their interaction, they prevent the adoption of less carbon-intensive transport modes and development pathways as well as ambitious individual and societal climate protection in the transport sector and beyond (Seto *et al.*, 2016).

At the same time, the awareness and commitment of individuals and society to environmental and climate protection is increasing in Germany against the backdrop of the looming consequences of climate change. A clear majority has a strong interest in climate protection and considers human activity to be the cause of climate change (BMU and UBA, 2019; UBA, 2021a). Correspondingly, a socio-ecological transformation of mobility, including respective measures and policies, meets with broad societal approval. The majority sees a great need for political action in this respect (UBA, 2021a). Likewise, the individual willingness to adopt environmentally aware and responsible behaviour such as for low-carbon mobility is increasing, albeit at a modest overall level and with clear differences in social milieus (BMU and UBA, 2019; UBA, 2021a). Particularly in large cities, first signs of an emerging mobility and transport transition can be discerned on the basis of changing mobility behaviour, usage preferences and new forms of transport services (Knie, 2013; Agora Verkehrswende, 2017; Lanzendorf and Hebsaker, 2017; Ruhrort, 2019, pp. 109 ff.). An urban *multimodal*⁸

⁷ *Carbon lock-in* describes a path-dependent process that leads to the persistence of technologies, institutions and behaviours locked into carbon emissions, that individually and in interaction constrain the rate of decarbonising system transformations, impede innovation and the diffusion of low-carbon alternatives (Unruh, 2000; Seto *et al.*, 2016).

⁸ *Multimodality* or *multimodal* mobility behaviour refers to the use of several means of transport by a person within a certain period of time (usually one week) in contrast to the *monomodal* use of a single means of transport (Nobis, 2015; Nobis and Kuhnimhof, 2018).

mobility culture is developing under comparatively good preconditions (in contrast to rural regions) such as comprehensive public transport systems, a dense urban form and infrastructure as well as better conditions for active travel (walking and biking) (Nobis and Kuhnimhof, 2018, pp. 58 ff.; Oostendorp *et al.*, 2019; Ruhrort, 2019, pp. 109 ff., 125 ff.; Schelewsky, Follmer and Dickmann, 2020, p. 56). This is also reflected in the higher proportion of urban households without a private car (Nobis and Kuhnimhof, 2018, pp. 34 f.). Ultimately, a shift towards multimodal mobility behaviour is apparent in large cities (Nobis and Kuhnimhof, 2018, pp. 58 ff.; Ruhrort, 2019, pp. 109 ff., 125 ff.), which entails more reduction options for the individual or household carbon footprint compared to the *monomodal* use of private cars (Schelewsky, Follmer and Dickmann, 2020, pp. 68 f.).

1.2 Approach, research objective and research questions

Against this background, the research project ‘Climate Neutral Living in Berlin’ (‘Klimaneutral leben in Berlin’, KLIB) of the Potsdam Institute for Climate Impact Research (PIK) aimed to identify to what extent and in what way urban households could reduce their carbon footprint through voluntary behavioural changes and measures on the basis of available technologies as well as existing living, market and policy conditions (Reusswig, Lass and Bock, 2020; Reusswig *et al.*, 2021). The main goal was to support and motivate private households to reduce their carbon footprint in all domains of household consumption and activity through a series of interventions in a one-year *real-world laboratory* (RwL) experiment. In addition, the scientists intended to find out which factors influence the adoption of reduction strategies and where the obstacles and limits to this adoption are (Reusswig, Lass and Bock, 2020; Reusswig *et al.*, 2021). The ‘real-world’ character of the experiment was shaped by the voluntariness of the actions to reduce emissions under existing options and opportunities and that neither monetary nor material incentives were provided to do so – the participants were supposed to act out of their own motivation and conviction, but with the clear goal of reducing emissions (Reusswig, Lass and Bock, 2020; Reusswig *et al.*, 2021). The core intervention simultaneously served for data collection: through a

carbon tracker online tool, households recorded their emissions-related activity and consumption behaviour in the domains of food, mobility, living or housing and other consumption throughout the year 2018. The year 2017 served as a reference via a baseline survey (Reusswig, Lass and Bock, 2020). Overall, the KLIB households managed to reduce emissions by about 11 % during the one-year real lab phase. Highest average emissions reductions were achieved in the domain of mobility, but there were also large differences in the CO₂-eq per capita emissions reductions among the households, in some cases even distinct increases in the carbon footprint (Reusswig, Lass and Bock, 2020).

Considering that households have different potentials and opportunities for emissions reduction depending on the households' living situation, individual preconditions for action as well as obstacles in the form of carbon lock-ins and other constraints, this study intends to enhance the understanding on the actual extent of emissions reductions through voluntary behavioural changes of private households in the field of mobility. Following the findings of Reusswig, Lass and Bock (2020) and based on the mobility data of the KLIB households, the research objective is to identify to what extent, in which domains of mobility and through which changes in mobility behaviour in terms of the use and demand of transport modes emissions reductions have been achieved under 'real-world' conditions. Since both mobility behaviour and carbon footprints are decisively influenced by the household living situation and its socio-demographic characteristics, it is reasonable in terms of pattern recognition to group the KLIB households according to relevant mobility-related household characteristics and to form types. Therefore, a mixed-methods research design is adopted: a transport sociologically grounded, qualitative approach of *empirically based type formation* will organise the KLIB households, creating the appropriate analytical access. A subsequent type-based descriptive statistical data analysis of the KLIB mobility data set will provide insights into changes of the types' mobility patterns and the associated emissions. According to the research objective, the overarching main research question and the two guiding research questions are the following:

Main research question:

To what extent do different urban household types reduce their household CO₂-eq emissions through voluntary action and changes in mobility behaviour towards low-carbon mobility forms and patterns within a real-world lab experiment?

Guiding research questions:

(1) To what extent do the different household types differ in their emissions reduction performance in the mobility domains ground mobility and air travel relative to the baseline and compared to other household types? [descriptive and comparative research]

(2) Through which changes in mobility behaviour in terms of modal choice and transport demand, in particular concerning car use and air travel, did the different household types achieve emissions reductions? Where are limits of voluntary efforts in this respect? [evaluation and explanatory research]

1.3 Structure

In order to address the objective of this study and to be able to adequately answer the research questions, a deeper understanding of the problem, the related issues, concepts and their background is needed. Accordingly, chapter 2 begins by outlining the challenge of decarbonising the transport sector in Germany (2.1) against the background of existing reduction targets, recent emissions development, their causes as well as current trends and projections (2.1.1). Subsequently, the relevance of the MPT and air travel as the main emissions drivers in passenger transport is considered on the basis of their transport performance and emissions intensity (2.1.2). Subchapter 2.2 first presents the potential of demand-side actions as relevant elements for emissions reductions (2.2.1). In this connection, the guiding concept of carbon footprint accounting is introduced (2.2.2). Based on this, an emissions reduction scenario compatible with the 1.5 °C target for lifestyle carbon footprints is presented and related to the average German carbon footprint (2.2.3). Subsequently, the implications of the household living situation, strategic consumption choices and associated carbon lock-ins on the household carbon footprint are highlighted (2.2.4). Subchapter 2.3 outlines

the path towards low-carbon mobility via required changes in the framework conditions (2.3.1), the presentation of strategic approaches to low-carbon mobility (2.3.2) and influencing factors of transport mode choice and mobility behaviour (2.3.3). Subchapter 2.4 introduces the experimental research approach of the real-world laboratories and their experiments for investigating sustainable societal transformations like the mobility transition. Finally, subchapter 2.5 describes the real-world lab experiment KLIB, its design, implementation (2.5.1) and results relevant to this study (2.5.2).

Chapter 3 describes the research design and methodology of the study: data collection within KLIB (3.1) includes the sampling or household recruitment (3.1.1) and a detailed description of the carbon tracker with respect to mobility as the core tool for household data collection (3.1.2). This is followed by the data preparation of the mobility dataset (3.2) comprising data aggregation (3.2.1), data cleansing and correction (3.2.2) as well as type formation (3.2.3) as the central method for structuring and organising the households' mobility data along mobility-relevant household characteristics. Subchapter 3.3 lastly describes the data analysis procedure, the statistical methods and calculations as well as the key figures and indicators.

Chapter 4 includes the results of the study, commencing with the characterisation of the sample (4.1) and the description of the frequency distribution of the mobility-related household types formed (4.2). Subchapter 4.3 comprises the results of ground mobility: first, the emissions balances and reduction performances of the types are described, compared with each other and referenced to the German average (4.3.1). This is followed by the presentation of the underlying modal choice and transport demand per household type as well as the derived comparison of individual transport modes within and between the main groups (4.3.2). Subchapter 4.4 covers the results on air travel, again comparing the emissions balances and differences of the types in reference to the German average. The emissions balances of ground mobility and air travel are lastly compared and integrated in subchapter 4.5, balanced concerning

effective total emissions reductions and broken down by contributions per transport mode.

In chapter 5, the results are interpreted, related to the research questions and discussed in connection with the research background and further relevant literature (5.1 and 5.2). Subsequently, the methodological limitations are highlighted, assessed and discussed in terms of their relevance and influence on the results of the study (5.3). Finally, in chapter 6, the findings and insights of the discussion are briefly synthesised and placed in their relevance in the overarching context which leads to the derivation of final conclusions and recommendations for action.

2 State of the problem, conceptual framework and research background

2.1 The carbon challenge of transport

2.1.1 European trends, German targets and emissions development

In the European Union (EU) GHG emissions from transport increased every year since 2014 and were estimated in 2018 to be 29 % above 1990 (EEA, 2020a). Also in 2019, emissions from the transport sector increased by approximately 0.8 %, contrary to the general trend of decreasing emissions in all other sectors (EEA, 2021). In fact, transport was the only major economic sector in the EU where GHG emissions have increased significantly since 1990 (EEA, 2020a). Overall, GHG emissions from transport including international aviation are responsible for around 25 % of total GHG emissions in the EU (EEA, 2020a). From an end user perspective transport is the largest emitting sector of energy-related GHG emissions in the EU (EEA, 2020b). National projections combined indicate that transport emissions will increase considerably again after the SARS-CoV-2 pandemic. Even with the measures currently planned in the member states, transport-related emissions in Europe will not fall below 1990 levels until 2029 (EEA, 2021).

Targets, current emissions development and projections in Germany

Germany has clearly committed to climate neutrality, confirmed its first reduction targets in 2016 with the Climate Action Plan 2050 (BMU, 2016) and the corresponding Federal Climate Change Act (KSG) in December 2019 (BMJV, 2019). Following the seminal ruling of the German Federal Constitutional Court (cf. BVerfG, 2021), the German Bundestag adopted the amendment to the Federal Climate Change Act on 24 June 2021, which commits Germany to climate neutrality by 2045 instead of the previous target of 2050 along concrete intermediate targets in reference to 1990 levels (BMJV, 2019; BMU, 2021). For the transport sector, a reduction of GHG emissions to 85 Mt CO₂-eq by 2030 was defined, which corresponds to 48 % less emissions compared to the reference year 1990 (BMU, 2021; UBA, 2021h, p. 17). However, until the SARS-CoV-2

pandemic, the transport sector did not show any effective contributions to climate protection: while all other sectors reduced emissions, CO₂-eq emissions from transport were 165,5 Mt in 2019, 0.4 % above the 1990 level (UBA, 2021e, 2021b, p. 73). In 2020, emissions from the transport sector fell significantly by 19 Mt CO₂-eq to around 146 Mt CO₂-eq, around 11 % less emissions compared to 2019 (UBA, 2021g). However, this decrease is attributable to the involuntary 'lockdown'⁹ measures and distinct rebound effects are already evident. Projections point to a strong increase in transport emissions for 2021 and a shortfall of the sector target (reduction to 145 Mt CO₂-eq) (Agora Energiewende, 2021; UBA, 2021g). Compared to the year 2020, there is a reduction gap of around 61 Mt CO₂-eq in relation to the climate protection target of 85 Mt CO₂-eq for 2030. The big, still unresolved question is how to close this gap. According to current projections, the present adopted measures in Germany will only achieve a reduction to around 126 Mt CO₂-eq in 2030 (UBA, 2021h, p. 30).

Problem sector transport – stagnating emissions and their reasons

The transport's emissions development in Germany over the last two decades unfolded against the backdrop of an increasing transport volume and transport performance of road transport. For example, the transport performance of MPT increased by around 9 % between 2006 and 2016 (BMVI, 2019, pp. 218 f.). The in average steadily growing vehicle fleet, increases in total transport performance and heavier and more powerful models negated efficiency gains in fuel consumption of new vehicles and vehicle types. In the long term, this has led to a stagnation of total emissions from road transport since 1990 (BMVI, 2019 p. 217 ff.; UBA, 2021b, pp. 213 f., 215). Road transport, especially the MPT, is responsible for the largest share of total transport-related emissions (Allekotte *et al.*, 2020, pp. 88, 122 f.; UBA, 2021b, pp. 213 f., 215 f.). Overall, road transport caused around 158 Mt CO₂-eq emissions in 2019, which equates to 95.5 % of total transport-related emissions (UBA, 2021b, p. 215). Meanwhile, the share of transport performance of low-carbon mobility alternatives such as local

⁹ The term 'lockdown' refers to the measures imposed during the SARS-CoV-2 pandemic, such as mandatory school closures and home confinement.

and long-distance public transport has hardly grown in relation to the MPT (BMVI, 2019, pp. 221 f., 228 f.). Yet at the same time, emissions from rail transport, for example, have fallen continuously since 1990 by a total of over 75 % to around 0.74 Mt CO₂-eq in 2019 (UBA, 2021b, pp. 220 f.). However, due to the small share in total transport performance, this has had no noteworthy mitigating effect on total transport emissions. Emissions from national aviation have actually decreased slightly compared to 1990 and amounted to around 2.2 Mt CO₂-eq in 2019 (UBA, 2021b, pp. 207 f.). In contrast, emissions from international air travel departing from Germany have risen steadily since 1990, in total by about 2.5 times to around 30 Mt in 2019, due to the continuously growing demand (UBA, 2021b, pp. 161 ff.; StBA, 2021). This increase in emissions would by now account for the second largest share in total transport emissions in Germany after the MPT. However, although emissions from international air travel departing from Germany are included in the inventory calculation, they are not considered part of the total national GHG inventory (UBA, 2021b, p. 160). In short, the considerable emissions of international air travel are neglected in the total accounting of national GHG inventories. This is a case of missing GHG emissions allocation and evidence that a source-based, territorial emissions inventory is insufficient to capture the actual climate impact of passenger transport or individual mobility (cf. Peters, 2008; Hertwich and Peters, 2009).

2.1.2 The main drivers of emissions in passenger transport

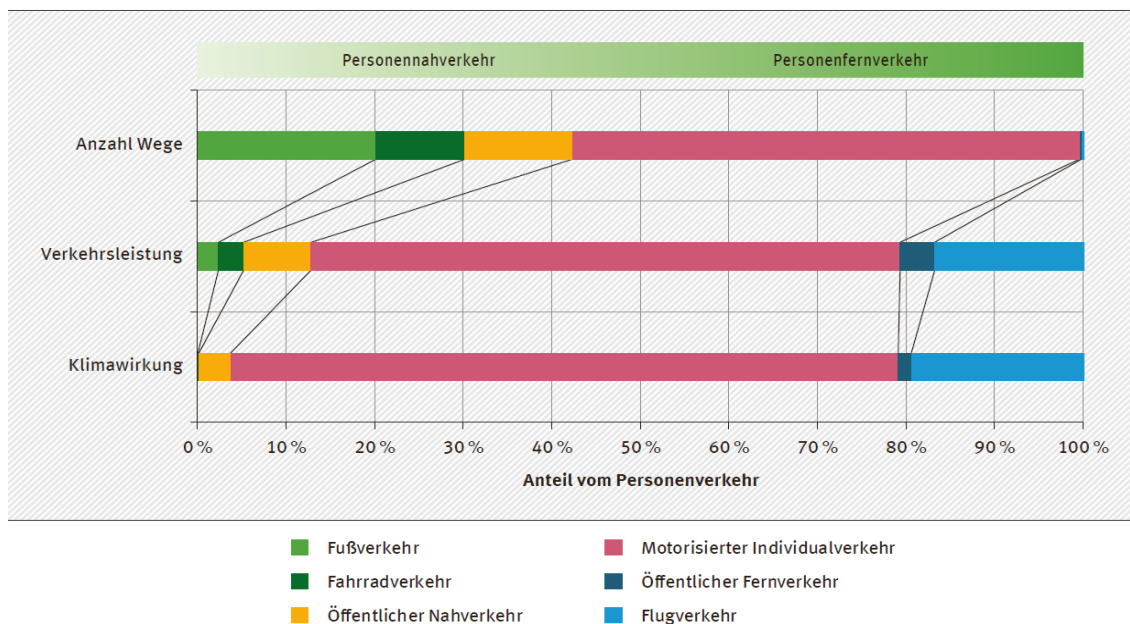
In passenger transport, the distance travelled, the emissions intensity per p-km of the means of transport and its occupancy rate are relevant factors (Allekotte *et al.*, 2021). Some modes of transport are rather used for short-distance or local transport, others for long-distance transport. In general, the longer the distance, the higher the emissions of GHG. However, the most emissions-intensive means of ground mobility, the private car, is used considerably for both short- and long-distance transport (Allekotte *et al.*, 2021).

The dominance of the MPT and the impact of air travel

The MPT, mainly represented by private cars, is consistently the dominant mode of transport in Germany, irrespective of whether the transport volume or the transport performance is considered. No other mode of transport moves more people or covers more p-km annually than the MPT (BMVI, 2019, pp. 217 ff.). The MPT has a share of 75 % of total transport performance, with an average occupancy of cars with 1.5 persons (Nobis and Kuhnimhof, 2018; Allekotte *et al.*, 2021). In contrast, the entire local and long-distance public transport is solely responsible for 14 % of total transport performance despite a considerably higher occupation capacity. The carbon neutral alternatives, walking and cycling, together account for 6 %, with almost equal shares. Domestic air travel accounts for 5 % of total transport performance (Nobis and Kuhnimhof, 2018; BMVI, 2019, p. 229). Not included in the consideration of national transport performance is international air travel. According to calculations by Allekotte *et al.* (2021), international long-distance air travel though would account for 17 % of total transport performance.

In the context of passenger transport emissions, the dominance of the MPT in terms of transport volume and performance is therefore problematic, but not on its own. *Figure 1* shows the relative climate impact (in percentage) of individual modes of passenger transport based on the shares of CO₂-eq emissions. According to Allekotte *et al.* (2021), the MPT is solely responsible for 75 % of CO₂-eq emissions from passenger transport. The second major driver is international air travel departing from Germany, which accounts for 19 % of CO₂-eq emissions (Allekotte *et al.*, 2021; UBA, 2021b, pp. 161 ff.). In contrast, local and long-distance public transport are much more climate-friendly alternatives. Together, they account for 14 % of transport performance, as described above, but only cause around 6 % of CO₂-eq emissions. The most climate-friendly modes of local transport are consequently walking and cycling (Allekotte *et al.*, 2021).

Bedeutung und Klimawirkung einzelner Verkehrsarten im Personenverkehr



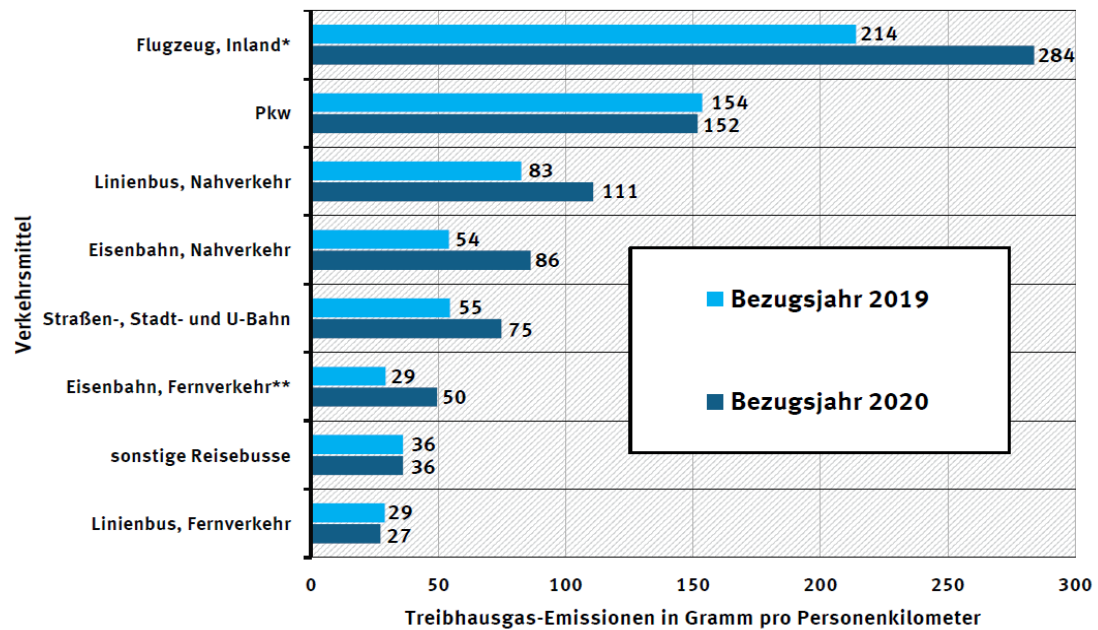
Anmerkungen: Werte für 2017

Quellen: Nobis (2019), Radke (2018), Statistisches Bundesamt (2018), Statistisches Bundesamt (2019), VDV (2019), eigene Berechnungen

Figure 1: Relevance and climate impact of individual modes of passenger transport. Shown are the number of trips, the transport performance and the associated relative climate impact (based on CO₂-eq emissions) of foot traffic (light green), bicycle traffic (dark green), local public transport (yellow), motorised private transport (pink), long-distance public transport (dark blue) and air travel (light blue) (reference year 2017, source: Allekotte *et al.*, 2021).

A direct comparison of the CO₂-eq emissions per p-km (CO₂-eq in g/p-km) of different means of transport in Germany, as illustrated in *Figure 2*, clearly identifies the MPT and air travel as the most emissions-intensive means of passenger transport. On average, MPT has 2–5 times higher CO₂-eq emissions per p-km than the means of public transport (buses and trains, cf. *Figure 2*) for the reference year 2019 (UBA, 2021d). However, if long-distance transport is considered, the climate impact in emitted CO₂-eq of air travel per p-km is in fact the highest, more than 7 times higher compared to long-distance rail transport for the reference year 2019 (cf. *Figure 2*; UBA, 2021d). The differences between the two reference years 2019 (light blue) and 2020 (dark blue) demonstrate the relevance of the occupancy rate of the means of transport for the emissions intensity per p-km: the fewer passengers, the higher the CO₂-eq emissions per p-km. In 2020, the public transport modes were markedly less occupied on average due to the ‘lockdown’ measures, which led to a correspondingly higher

emissions intensity per p-km. Consequently, this is most pronounced for the most emissions-intensive mode of transport, air travel (cf. Figure 2; UBA, 2021d).



g/Pkm = Gramm pro Personenkilometer; CO₂, CH₄ und N₂O angegeben in CO₂-Äquivalenten inkl. der Emissionen aus Bereitstellung und Umwandlung der Energieträger in Strom, Benzin, Diesel, Flüssig- und Erdgas sowie Kerosin
 * inkl. Nicht-CO₂-Effekte
 ** Die in der Tabelle ausgewiesenen Emissionsfaktoren für die Bahn basieren auf Angaben zum durchschnittlichen Strom-Mix in Deutschland. Emissionsfaktoren, die auf unternehmens- oder sektorbezogenen Strombezügen basieren (siehe z. B. den „Umweltmobilcheck“ der Deutschen Bahn AG), weichen daher von den in der Grafik dargestellten Werten ab.

Quelle: Umweltbundesamt, TREMOD 6.21 (11/2021)

Figure 2: Comparison of the average GHG emissions [in g CO₂-eq/p-km] of individual means of passenger transport in Germany. Means of transport from top to bottom: plane (domestic), passenger car, public bus (short distance), short-distance railway, local and urban railway, long-distance railway, coach, public bus (long-distance) (for reference year 2019 (light blue) and 2020 (dark blue), source: UBA, 2021d).

The non-CO₂ effects of air travel

Emissions from air travel are such emissions-intensive due to a complex chain of effects. The growing travel distance and thereby especially the flight altitude play a decisive role. Besides CO₂, air travel produces other emissions that have a relevant effect on the climate: these are primarily water vapour, particles, sulphur and nitrogen oxides (Allekotte *et al.*, 2020, pp. 62, 122 ff.; Lee *et al.*, 2021; UBA, 2021b, pp. 207 ff.). Water vapour (H₂O) leads to the formation of vapour trails and, together with particles that act as cloud condensation nuclei, cirrus clouds are formed that cause additional radiative forcing. Nitrogen oxides (NO_x) influence the formation of the GHG ozone (O₃) (Lee *et al.*, 2021). Since the emissions are introduced directly into higher

atmospheric layers, their radiative forcing or 'climate impact' differs significantly from emissions near the ground. The atmospheric conditions, which change with flight altitude, are important in this relation: the main influencing factors are atmospheric pressure, ambient temperature and humidity (Lee *et al.*, 2021; UBA, 2021b, pp. 207 f.). These *non-CO₂ effects* and their impact on the climate thus depend strongly on the flight altitude and the atmospheric conditions there, and consequently increase with the length of the flight (Lee *et al.*, 2021; UBA, 2021b, pp. 207 f.). Overall, these non-CO₂ effects amplify the climate impact of air travel by a factor of 2–3 compared to the pure CO₂ emissions (Allekotte *et al.*, 2020, pp. 62, 123; Lee *et al.*, 2021). On global scale, pure CO₂ emissions from aviation currently account for about 2.5 % of total CO₂ emissions. If the non-CO₂ effects are included, the share of global GHG or CO₂-eq emissions from aviation is estimated to rise to 5–8 % (UBA, 2019; Larsson *et al.*, 2019; Allekotte *et al.*, 2020, p. 123; Lee *et al.*, 2021).

In this context, the strong growth of aviation is problematic, with estimates that emissions have increased by a factor of 6.8 since 1960 to 2018 (Lee *et al.*, 2021). Currently, experts expect the aviation industry to recover with a strong upward trend after the SARS-CoV-2 pandemic, as after previous crises (DLR, 2020). The International Transport Forum (ITF, 2021) estimates aviation should reach 2019 levels by around 2023 and projects in a post-SARS-CoV-2 recovery scenario that air travel will experience the largest relative growth in passenger transport by 2050, increasing by a factor of 3.5 compared to 2015. If this were to happen, the aviation sector would be increasingly in conflict with global decarbonisation. Especially considering the fact that there are very limited technical or management options to shape air transport more climate-friendly (Peeters *et al.*, 2016).

For example, CO₂-neutral synthetic fuels produced from renewable energy would offset the CO₂, but the non-CO₂ effects would remain (UBA, 2019).

In the following subchapter, the potential of lifestyle and behaviour changes for the decarbonisation of society is highlighted, in particular concerning transport and mobility. Correspondingly, the concept of carbon footprint accounting is introduced and

an emissions reduction scenario with targets for lifestyle carbon footprints is presented. Subsequently, the implications of the household living situation and its socio-demographic factors on the carbon footprint are addressed, considering the varying potential and opportunities of households to reduce emissions, especially with respect to strategic decisions, structural constraints and associated carbon lock-ins.

2.2 Lifestyle and behavioural change for emissions reductions

2.2.1 Considering the potential of demand-side actions

In its special report on global warming of 1.5 °C, the IPCC emphasized once more, the potential of demand-side actions such as behavioural, consumption and lifestyle changes as a key elements to support the achievement of the 1.5 °C pathway (Rogelj *et al.*, 2018, pp. 97, 161). Different studies assess that 60–72 % of global GHG emissions are attributable to household consumption patterns and lifestyles (Hertwich and Peters, 2009; Ivanova *et al.*, 2016). Accordingly, behavioural changes and the shift towards low-carbon lifestyles, especially in the domains nutrition, housing and mobility, can achieve rapid and considerable emissions reductions, notably in high-income countries like in Europe or North America (Dietz *et al.*, 2009; Dubois *et al.*, 2019; IGES, Aalto University and D-mat ltd., 2019; Vita *et al.*, 2019; Costa *et al.*, 2021). A recent study covering the EU consistently showed that behavioural changes alone could contribute to more than 20 % of the total GHG emission reductions needed to reach the EU's net-zero target by 2050. Yet, the combination of ambitious behavioural and technological changes would even enable net-zero emissions to be achieved already by approximately 2040 with synergetic-complementary effects particularly evident in the transport sector (Costa *et al.*, 2021). Behavioural changes are furthermore emphasised as decisive in terms of timeliness and cost-effectiveness, as they can deliver faster and more cost-efficient emissions reductions than technological changes (Creutzig *et al.*, 2016; Costa *et al.*, 2021). Indeed, extent and time are relevant factors in the light of current trends and emissions pathways that indicate a global average temperature increase between 2.4 and 2.7 °C by 2100 (CAT, 2021; UNEP, 2021). Delaying action will lead to increased costs, lost assets and reliance on technologies that

could potentially conflict with sustainability (IPCC, 2018, p. 18). Yet, despite the extent and rapid mitigation potential of demand-side actions, the discussion on solutions to climate change was long time primarily focused on technology (Akenji and Chen, 2016; Creutzig *et al.*, 2016, 2018).

The majority of existing emissions scenarios and reduction pathways are based on source- or production-based emissions accounting as well as corresponding technological reduction measures. National GHG inventory reporting and sector-specific climate protection programmes and targets are examples of that (cf. for Germany: BMU, 2016, 2019; UBA, 2021b). However, the behavioural and consumption-based approach, considering the activity and consumption of individuals and households, but also of companies and organisations, is increasingly gaining scientific attention (cf. Schächtele and Hertle, 2007; Hertwich and Peters, 2009; Akenji and Chen, 2016; Greiff *et al.*, 2016; Ivanova *et al.*, 2016; Kleinhüchelkotten, Neitzke and Moser, 2016; Schanes, Giljum and Hertwich, 2016; Salo and Nissinen, 2017; IGES, Aalto University and D-mat Ltd., 2019; Ivanova *et al.*, 2020). Correspondingly, mitigation pathways scenarios have recently been developed that include demand-side reduction measures using consumption-based emissions accounting in order to correctly quantify the impact of lifestyles, behaviours and consumption patterns (Van Vuuren *et al.*, 2018; IGES, Aalto University and D-mat Ltd., 2019).

2.2.2 Carbon footprint accounting

The traditional concept of emissions accounting is the territorial- or production approach based on source balancing (cf. Munksgaard and Pedersen, 2001). However, it neglects indirect or embedded emissions from international trade and transportation of imported products and services as well as emissions from international aviation, which eventually can lead to carbon leakage or lack of emissions allocation (cf. Schächtele and Hertle, 2007; Peters and Hertwich, 2008; Hertwich and Peters, 2009). It is therefore insufficient to capture the true emissions balance of individuals and households (Schächtele and Hertle, 2007; Peters and Hertwich, 2008).

In contrast, a consumption-based approach to emissions accounting considers direct and indirect or embedded GHG emissions along the entire value chain from production, distribution until the final consumption of products and services, thereby also addressing the problem of carbon leakage and resolving allocation issues (cf. Munksgaard and Pedersen, 2001, Peters, 2008; Peters and Hertwich, 2008). Consequentially, it holistically maps the impact of individuals' lifestyles and consumption, but also of international companies and organisations (Schächtele and Hertle, 2007; Peters and Hertwich, 2008; IGES, Aalto University and D-mat Ltd., 2019). Correct allocation of emissions opens up decisive further mitigation options such as lifestyle and behavioural changes at the individual or household level (Schächtele and Hertle, 2007; Peters and Hertwich, 2008). However, this also means that individuals are held co-responsible for the emissions caused by their lifestyle and consumption choices, alongside companies and governments.

Lifestyle carbon footprints

Linked to the environmental footprint concept, the consumption-based accounting principle of *carbon footprints* emerged (cf. Hoekstra and Wiedmann, 2014). The *carbon footprint* refers to the direct and indirect GHG emissions generated by activities or products over their entire life cycle. It can be applied to products and processes as well as to daily activities of individuals or organisations whether in the form of households, companies or countries (cf. Wiedmann and Minx, 2008). The *lifestyle carbon footprint* refers specifically to the activities and consumption of individuals and households. Accordingly, the *lifestyle carbon footprint* is defined as the total of direct (e.g. from the use of fuels) and indirect (e.g. embedded emissions in products and services) GHG emissions from household consumption or activity (IGES, Aalto University and D-mat Ltd., 2019). *Figure 3* compares the different presented concepts of GHG accounting. The consumption-based carbon footprint approach formed the basis of the data collection within the KLIB project, additionally factoring in the individuals' share

of public emissions (e.g. public infrastructure, police, etc.) (Reusswig, Lass and Bock, 2020). Consequently, it also constitutes the guiding concept of this study.

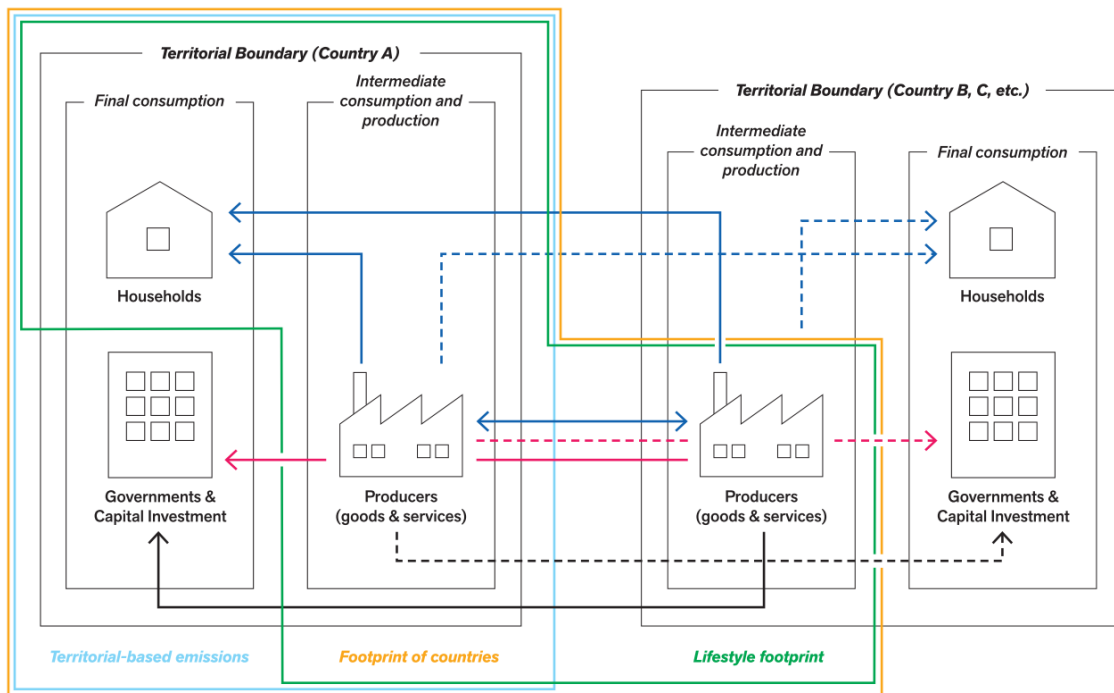


Figure 3: Comparison of the territorial, production-based GHG emissions accounting and the consumption-based footprint accounting. The solid and dashed arrow lines describe the national and international value chains and the associated emissions from production, distribution/transport and consumption (source: IGES, Aalto University and D-mat ltd., 2019).

2.2.3 The low-carbon lifestyle pathway and its carbon footprints

The Institute for Global Environmental Strategies (IGES), Aalto University and D-mat ltd. (2019) examined current consumption patterns and their impacts on the carbon footprints in developed and developing countries and evaluated the reduction potential through low-carbon lifestyle options in the relevant fields of household consumption and activity. On that basis they established global targets for carbon footprints along emissions reduction scenarios compatible with the 1.5 °C target of the Paris Agreement. They proposed lifestyle carbon footprint targets of 2.5 t CO₂-eq by 2030 and 0.7 t CO₂-eq by 2050 (IGES, Aalto University and D-mat ltd., 2019). However, there are large gaps between the targets and current lifestyle footprints. For comparison, the current average German carbon footprint amounts to around 11.2 t CO₂-eq per

capita and year (UBA and KlimAktiv, 2020d). With respect to the gap between the current and the target lifestyle carbon footprints there is a need for reduction by 80–93 % by 2050 for developed countries. This relates to an immediate annual reduction rate of 8–12 % (IGES, Aalto University and D-mat Ltd., 2019). Assuming an annual reduction rate of 10 %, this corresponds to an average reduction of the German carbon footprint by 1.1 t CO₂-eq per capita and year.

IGES, Aalto University and D-mat Ltd. (2019) also found emissions hotspots in their analysis of the activity and consumption patterns of households, which are located in the domains of nutrition, housing and mobility. Specifically, meat and dairy consumption, fossil fuel energy, car use and air travel are the domains where efforts should be focused to reduce emissions or carbon footprints the most (IGES, Aalto University and D-mat Ltd., 2019). These results are consistent with several comparable studies if ‘other consumption’ of goods and services is included as another major cause of emissions, especially in developed countries (cf. Hertwich and Peters, 2009; Greiff *et al.*, 2016; Ivanova *et al.*, 2016; Salo and Nissinen, 2017; Dubois *et al.*, 2019; Reusswig, Lass and Bock, 2020). IGES, Aalto University and D-mat Ltd. (2019) further identified a particular need for action to reduce the carbon footprint reduction in the field of mobility. In relation to the defined target carbon footprints, a reduction of 72 % by 2030 and a reduction of 96 % of the carbon footprint by 2050 would be necessary for developed countries like Germany (IGES, Aalto University and Ltd., 2019).

Mobility from a German carbon footprint perspective

In a consumption-based carbon footprint perspective, each German emitted an average of around 11.6 t CO₂-eq in 2018, of which 2.18 t CO₂-eq or 19 % were attributable to mobility. Of this, 1.6 t CO₂-eq or 73 % were again attributable to ground mobility and 0.58 t CO₂-eq or 27 % to air travel (Reusswig, Lass and Bock, 2020, via UBA Carbon Calculator, retrieved 2019). For comparison, as illustrated in *Figure 4*, a passenger car emits an average of 2.4 t CO₂-eq per year. For a round-trip flight from Berlin to Majorca, 0.72 t CO₂-eq per person are emitted, for a flight to New York, 3.16 t CO₂-eq per

person. A person who flies from Berlin to Sydney and back accounts for 10.71 t CO₂-eq emissions in a single trip, which is almost as much as the average German citizen emits in a whole year (UBA, 2019). Air travel as a mode of transport or considered as a single activity in a consumption perspective of individuals, has the most emissions-intensive impact on the personal or household carbon footprint (Allekotte *et al.*, 2020, p. 123; Ivanova *et al.*, 2020; Gössling, 2021).

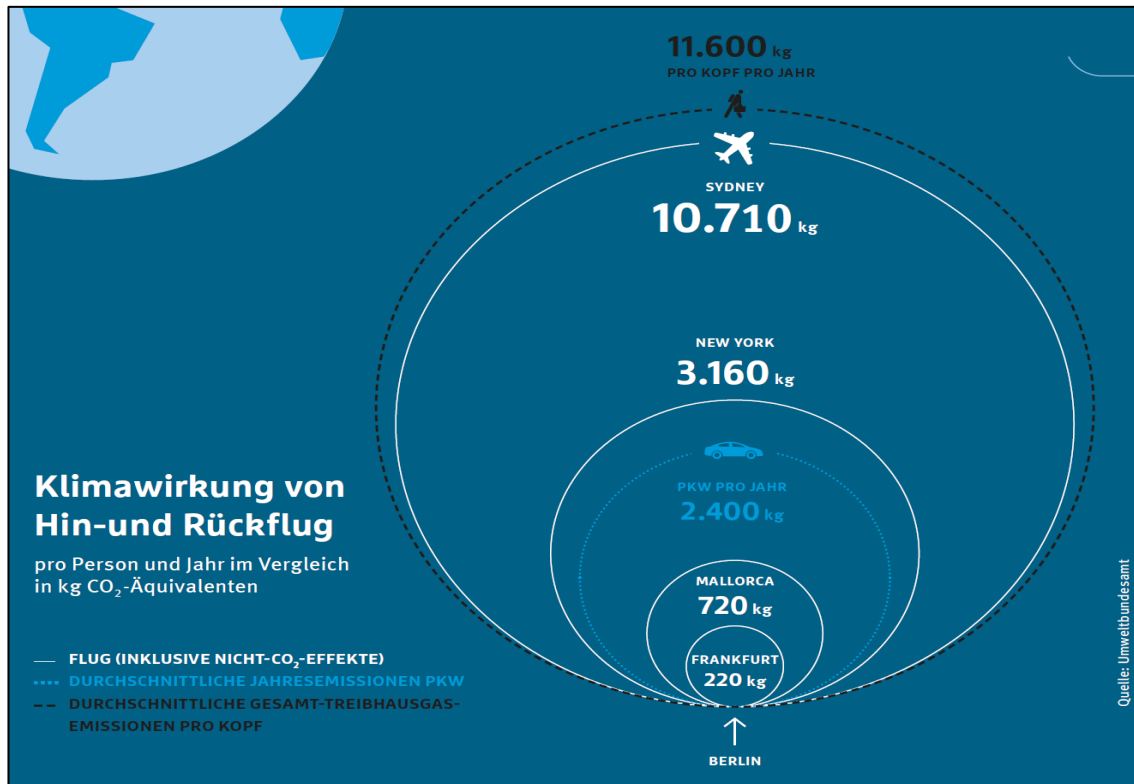


Figure 4: Comparison of the climate impact [in kg CO₂-eq/person/year] of different round-trip flights per person with the average annual per capita emissions and the average annual emissions of a car in Germany (source: UBA, 2019).

On the individual or household level, it is therefore scientifically indisputable that, on the one hand, the private car and air travel are among the largest single drivers of the carbon footprint and that, on the other hand, their impact can ‘theoretically’ be relatively easily reduced through behavioural changes. Thus, refraining from a private car or reducing air travel and shifting to low-carbon modes of transport bears the highest emissions reduction potential in the domain of mobility (Dietz *et al.*, 2009; Akenji and Chen, 2016; IGES, Aalto University and D-mat ltd., 2019; Dubois *et al.*, 2019; Vita *et al.*, 2019; Ivanova *et al.*, 2020). However, with a current average carbon

footprint of about 11.2 t CO₂-eq per capita and year and around 2.1 t CO₂-eq (19 %) alone attributable to mobility (UBA and KlimAktiv, 2020d), Germany is far from the per capita footprint targets proposed by IGES, Aalto University and D-mat ltd. (2019).

2.2.4 Implications of the household living situation and carbon lock-ins

Households are manifold, however, their carbon footprint is decisively influenced by the *household living situation* and its socio-demographic characteristics (Kleinhüchelkotten, Neitzke and Moser, 2016; Miehe *et al.*, 2016; Dubois *et al.*, 2019). Minx *et al.* (2013) found that household carbon footprints increase with growing income, education and car ownership as well as decreasing household size. Other studies come to similar conclusions with regard to socio-demographics and vehicle equipment: household footprints vary first and foremost depending on income level (Cohen, Lenzen and Schaeffer, 2005; Lenzen *et al.*, 2006; Boucher, 2016; Miehe *et al.*, 2016; Ivanova *et al.*, 2018; Dubois *et al.*, 2019; Ivanova and Wood, 2020; Schelewsky, Follmer and Dickmann, 2020; Jack and Ivanova, 2021), car ownership (Ornetzeder *et al.*, 2008; Jones and Kammen, 2014; Ivanova *et al.*, 2018), household size (Ala-Mantila, Heinonen and Junnila, 2014; Miehe *et al.*, 2016; Dubois *et al.*, 2019; Jack and Ivanova, 2021) and level of education (Kleinhüchelkotten, Neitzke and Moser, 2016; Ivanova *et al.*, 2017; Ivanova and Wood, 2020).

A recent study on the carbon footprints of Danish households found that small household sizes are a key challenge for emissions reductions: single (42 %) and couple households (34.9 %) together account for around 77 % of the Danish carbon footprint. The highest-income single households also showed the highest per capita footprint, with transport accounting for the largest share of it. Conversely, the per capita footprint decreased with increasing household size and decreasing income (Jack and Ivanova, 2021). Ivanova and Büchs (2020) came to similar results: in an examination of households across EU countries, they identified one-person households as the most carbon-intensive per capita (average of 9.2 t CO₂-eq/person), closely followed by two-person households (average of 8.4 t CO₂-eq/person). The lowest carbon footprints consequently showed multi-person households (>4 persons; average of 4.6 t CO₂-

eq/person) with about the half compared to that of one-person households (Ivanova and Büchs, 2020). In addition, a comprehensive analysis of household consumption data by Ivanova and Wood (2020) revealed that EU household carbon footprints are unequally distributed among socio-economic groups. The households with the highest carbon footprints are those with the highest income and expenditure, and with the greatest carbon contribution from air travel and land transport (Ivanova and Wood, 2020). Combined, these results demonstrate that high-income single and couple households are of specific relevance concerning their emissions and carbon footprints.

Strategic consumption decisions and carbon lock-ins

Household carbon footprints are thus largely defined by the household living situation and its socio-demographic characteristics. Accordingly, the households' living situation has a strong influence on the potential and opportunities of households to reduce their carbon footprint (Dubois *et al.*, 2019). Carbon footprints of households are therefore conceptually not static. They change with the household living situation, with the socio-demographic characteristics which describe the latter and the decisions that shape it. In fact, however, there are key moments of 'strategic consumption decisions' (cf. Bodenstein, Spiller and Elbers, 1997) that vary in their temporal persistence and path dependency but can have a significant impact on the carbon footprint – such as where to live (e.g. city centre, outskirts or country side), whether to build a house or live in an apartment house, buy a car or travel by plane (Jones and Kammen, 2014; Dubois *et al.*, 2019). These strategic consumption decisions are in turn influenced by the households' living situation or socio-demographics. For example, a young couple household will only move to the denser city centre with a better transport infrastructure when they can afford it. Conversely, a growing family household might move into a larger house or flat at the outskirts and consider purchasing a car to commute safely with young children. However, a key determining factor for reduced emissions is settlement density, while car ownership and longer distances are correlated with greater carbon footprints (Jones and Kammen, 2014; Ivanova *et*

al., 2018). Accordingly, emissions reductions through behavioural change and demand-side actions can be challenging depending on the household living situation, *carbon lock-ins* and structural constraints (Ivanova *et al.*, 2018). There are different types of technological, infrastructural, institutional and behavioural carbon lock-ins which interfere or impede with behavioural change (cf. Seto *et al.*, 2016). At the household level, *car ownership* in particular is a significant (technological) carbon lock-in with a high probability of driving the vehicle, even for short distances (Ivanova *et al.*, 2018). In addition, there are associated ‘lock-in effects’ of individual behaviours that are particularly apparent in routinised, habitual travel behaviour (Seto *et al.*, 2016). Given that car drivers are more affected by their travel habits than public transport users (Donald, Cooper and Conchie, 2014), behavioural lock-in in terms of MPT is a clear barrier for carbon emissions reductions (Seto *et al.*, 2016). Technological and behavioural carbon lock-ins are correspondingly interconnected and interdependent and consequently need to be addressed jointly through policies that systematically target behavioural and technological change as a whole (Seto *et al.*, 2016).

In the following subchapter, the necessary change in the framework conditions for low-carbon mobility is addressed. Subsequently, strategic approaches to low-carbon mobility are presented and the ways in which they can be transferred and applied to the mobility behaviour of individuals. Lastly, mobility behaviour and its influencing factors with regard to transport mode choice are outlined in the light of its habitual and routinised character.

2.3 Towards low-carbon mobility

2.3.1 The change of the framework conditions

Currently, Germany is still dominated by a car-centralised transport system, which at the infrastructural and technological level through its longevity and path dependency, itself represents a comprehensive *carbon lock-in* that perpetuates society’s carbon-intensive emissions pathways and prevents a shift towards low-carbon mobility (Seto *et al.*, 2016; Canzler *et al.*, 2018; Canzler and Knie, 2019). Furthermore, the long-

term growth in air travel, especially international air travel, increases the pressure and challenges on the decarbonisation of the transport system (cf. section 2.1; UBA, 2021b, p. 161 ; ITF, 2021; StBA, 2021). In addition, there are still policy measures and environmentally harmful subsidies that substantially promote motorised transport and air travel, distorting competition against low-carbon alternatives and counter-acting climate and environmental policy instruments (Burger and Bretschneider, 2021). They constitute another form of institutional and governance carbon lock-ins, however conversely, they are also levers to induce change (Seto *et al.*, 2016).

Behavioural change is an essential element for the success of the mobility transition and the decarbonisation of the transport sector. However, lifestyle and behavioural changes can only unfold their full emissions reduction potential if there is an appropriate low-carbon infrastructure supporting the shift to low-carbon modes of transport (Creutzig *et al.*, 2016; Javaid, Creutzig and Bamberg, 2020). In concrete terms, this means above all a fast, attractive and affordable public transport system, a comprehensive bike route network, dense urban planning for short distances that encourages active travel as well as an area-wide charging infrastructure for e-mobility, sharing e-mobility options and services (cf. Agora Verkehrswende, 2020; UBA, 2021h). The shift to low-carbon transport could then incrementally be promoted and advanced by changing perceptions of common travel behaviour in the form of collective social norms for low-carbon mobility practice (Creutzig *et al.*, 2016; Javaid, Creutzig and Bamberg, 2020). However, establishing new social norms also requires appropriate policy instruments that support low-carbon mobility practice (Creutzig *et al.*, 2016; Nyborg *et al.*, 2016; Javaid, Creutzig and Bamberg, 2020). Social equity concerning the varying potential and opportunities of diverse households to reduce their carbon footprint in relation to differences in the household living situation (income, household size, etc.) should be considered. At the moment, households receive insufficient attention in current climate policy strategies given their relevance (Dubois *et al.*, 2019). Accordingly, regulatory frameworks need to be changed and policy instruments to be established that purposefully remove technological and infrastructural carbon lock-ins, create strong incentives to disentangle from behavioural lock-ins

and steer behavioural change towards low-carbon lifestyles (Seto *et al.*, 2016; Creutzig *et al.*, 2018; Ivanova *et al.*, 2018; Dubois *et al.*, 2019).

2.3.2 Strategies for low-carbon mobility behaviour

Strategic approaches that address both the carbon problem and other environmental and social problems have long been an integral part of the social and transport science discourse (cf. Banister, 2008; Bongardt *et al.*, 2013). Scenarios dealing with the sustainable transformation of the mobility and transport system distinguish between three basic strategies to achieve low-carbon mobility: the *avoid – shift – improve* (ASI) approaches (Bongardt *et al.*, 2013, pp. 45 ff.; Ruhrort, 2019, pp. 28 ff.; ITF, 2021).

Avoid – Shift – Improve

Essentially, the objective is to *avoid* transport or to reduce the demand for it, to *shift* transport towards low-carbon modes and to *improve* the associated technologies (Bongardt *et al.*, 2013, pp. 45 ff.). It is the combination of the three approaches that is, in principle, expected to have a sufficiently strong effect on reducing emissions as well as solving other environmental, social and spatial issues (ITF, 2021). Yet the *improve* approach with its technological focus dominates current policies and measures, particularly targeting the conversion of the MPT towards new energy efficient drive systems, alternative or low-carbon fuels and operational efficiency (Ruhrort, 2019, pp. 29 f.; ITF, 2021). However, it also generates undesirable *rebound effects*¹⁰ creating transport growth, which diminish or even offset emissions savings and efficiency gains (Sanatorius, 2012). The *avoid* approach is primarily focused on measures to reduce transport activity through an integrated transport-saving spatial, urban planning and transport demand management. The objective is a dense city and smart infrastructure planning of short trips, also increasing the potential of *modal shift*

¹⁰ *Rebound effects* are undesirable side effects in the form of increased demand for energy as a result of productivity or efficiency increases, which counteract the actual objective of saving energy. The additional demand due to an increase in productivity is referred to as the *rebound effect*. A distinction can be made between indirect and direct as well as financial, material and psychological rebound effects (Sanatorius, 2012).

(Bongardt *et al.*, 2013, p. 48). The *shift* approach in turn aims at shifting transport away from energy-intensive forms like the MPT towards the more efficient, low-carbon modes of public transport and active modes like walking and biking, referred to as *modal shift*. Collectively also referred to as the 'environmental alliance' (Bongardt *et al.*, 2013, pp. 48 f.; Ruhrort, 2019, pp. 29 f.). The shift approach relates most strongly to behavioural changes of individuals and is therefore the most relevant for this study, also due to its short-term applicability in the scope of households. However, as well shift strategies can lead to rebound effects, e.g. in the form of transport growth through an increased attractiveness of public transport (cf. Rammler, 2016, p. 907; Ruhrort, 2019, p. 30). Moreover, indirect psychological rebound effects such as the *moral-licensing-effect* can be of relevance in shift strategies. In this case, the purchase or consumption of an ecological product or service could be considered as a justification and permission for the consumption of an environmentally harmful product or service, as a form of moral compensation or balancing (cf. Sanatorius, 2012).

Examples of ASI applications on the household level

On the individual or household level of mobility, these higher-level transport science approaches can be converted into straightforward emissions reduction strategies with partly strong impacts on the carbon footprint.

Avoid. As a general rule, every avoided motorised trip also does not cause any emissions. Car and motorbike owners might therefore ask themselves whether the respective motorised trip or journey is really necessary or whether it can be avoided. Examples are one extended holiday trip instead of several weekend trips or working remotely in home office instead of steady commuting to the office or conferences (Allekotte *et al.*, 2021). Video conferencing and home office can make a significant contribution to reducing CO₂-eq emissions. In Germany, 195 million work-related trips took place in 2019, the majority of which were made by car or plane. During the first 'lockdowns' in 2020 due to the SARS-CoV-2 pandemic, video conferencing and home office took the place of business travels. In this regard, a study based on a

survey of business travellers showed that if the changed business travel patterns were maintained proportionately after the pandemic, as expected by the respondents and if there were no significant rebound effects, this could save approximately 3 Mt CO₂-eq annually (Clausen and Schramm, 2021). Journeys by plane are better to be avoided if the destination can be reached by other means of transport, e.g. by train or coach. Especially for long-distance journeys, where the plane is usually the only alternative, it might be questioned whether this journey is really necessary or whether a closer destination might do as well. It is clear that those who have the mobility option of a private car or another motorised vehicle will also use it (cf. section 2.2.4, *carbon lock-in of car ownership*). Thus, those who avoid purchasing a private car, especially one with an internal combustion engine, save considerably on direct and indirect emissions (cf. section 2.1.2).

Shift. For unavoidable trips and journeys, the environmental alliance could be used as much as possible, i.e. a shift away from MPT towards local public transport and bike in short-distance transport and train in long-distance transport. In urban transport, the bike is often even the most efficient means of transport. In German cities, 40–50 % of car trips are less than 5 km. In this distance range, the bike is the fastest and most cost-efficient means of transport (UBA, 2021f). If one cannot do without a motorised drive, car-sharing, ride-pooling and other sharing offers in cities are reasonable alternatives to the private car (cf. Agora Verkehrswende, 2020). Domestic short-haul flights are unnecessary, as these can easily be shifted to railway service.

Improve. If one cannot do without a private car at all, the most effective way to improve the carbon footprint would be to replace an internal combustion car with an electric car in the long term (Ivanova *et al.*, 2020). In addition, emissions per person decrease with higher occupancy of vehicles (Bongardt *et al.*, 2013, p. 48). The more people use a vehicle simultaneously, the more energy-efficient and less carbon-intensive it will be per p-km (cf. *Figure 2*). Therefore, in addition to the predominantly electric drive in rail transport, public transport is especially due to the higher occupancy capacities and rates of the vehicles more energy- and emissions-efficient than

the MPT (Bongardt *et al.*, 2013, pp. 48, 51 f.; Allekotte *et al.*, 2021). A car has an average occupancy of 1.5 persons. Carpooling and ride-sharing concepts based on digital information systems bundle trips and journeys and thus reduce emissions (Allekotte *et al.*, 2021).

A recent meta-study that systematically examined 61 options for reducing emissions from household consumption in the relevant domains (food, housing, transport, other consumption) condenses the essentials: the options with the highest mitigation potential are found in the domain of transport. These options include living car-free, shifting to a battery electric vehicle, reducing or refraining from air travel as well as a shift towards less carbon intensive fuel sources, means and modes of transport (Ivanova *et al.*, 2020).

2.3.3 Transport mode choice and mobility behaviour as a routine

Mobility behaviour, and thus the choice and demand of transport modes, is essentially based on 'free decisions' (Busch-Geertsema *et al.*, 2016, p. 766). However, there is a multitude of influencing factors that can be divided into structural framework conditions and individual preconditions for action (Scheiner, 2016, pp. 684 ff.). In the household context, the focus is on the individual living situation and the availability of means of transport with respect to the individual preconditions. With regard to the structural framework conditions, the spatial and settlement structure as well as the transport systems are of relevance (Scheiner, 2016, p. 684). Mobility behaviour is usually based on the principle of utility maximisation (cf. Scheiner, 2016, p. 685), whereby the term 'utility' is largely extended in the direction of convenience, independence, flexibility, safety, privacy, speed and efficiency. According to this logic, the individual transport decision depends specifically on the available choice alternatives (e.g. available transport modes, spatial structure), the current action situation (e.g. trip purpose, weather), individual preferences and preconditions of action, which can be mapped by socio-demographic characteristics (e.g. income, gender, age etc.) (Scheiner, 2016, p. 685). Mobility behaviour and thus the choice of means of transport is a complex everyday situation, as shown by the numerous influencing factors. As it is a recurring,

everyday practice it is habitualised and not reconsidered and decided on a daily basis, taking into account all available information and weighing up various options. Hence, although the transport mode choice is essentially a 'free decision' situation, it is significantly shaped by habits and routines (Busch-Geertsema *et al.*, 2016, p. 766; Knie, 2016, p. 37). Mobility habits or routines reduce the information needed to make decisions on how and with which means of transport to reach a destination (cf. Aarts, Verplanken and Knippenberg, 1997; Busch-Geertsema *et al.*, 2016, p. 766). Habits or routines can constitute relatively stable behaviour when they occur in stable contexts as in everyday mobility (Danner, Aarts and Vries, 2008). If so, they are barely influenced by intention and characterised by a low level of attention and information seeking regarding alternatives (Danner, Aarts and Vries, 2008; Verplanken *et al.*, 2008). The transport mode choice consequently arises from a complex mix of influencing factors, habits and routines and therefore cannot be changed by measures that target spontaneous decisions (Knie, 2016, p. 49).

As already outlined in section 2.2.4 (*carbon lock-ins*), routines and travel habits related to car use can form strong behavioural lock-in, which constitutes a barrier to emissions reductions in the household context (cf. Seto *et al.*, 2016; Ivanova *et al.*, 2018). In this respect, the acquisition of a private car is also less of an 'influencing factor' for the transport mode choice in everyday mobility behaviour, but rather a 'transport mode pre-decision' with a longer-term horizon, leading to a modal path dependency and carbon lock-in (Scheiner, 2016, p. 694; Ivanova *et al.*, 2018).

Context changes for behavioural change

However, there are successful interventions that are consistent with the habit-discontinuity hypothesis (cf. Verplanken *et al.*, 2008), which states that behaviours are more flexible or adaptable when a 'context change' (in terms of physical, spatial, temporal or social factors that influence behaviour) disrupts the routine or habits (Verplanken *et al.*, 2008). During this context change, a 'window of opportunity' of increased attention opens up in which decisions are made more consciously, guided

by intention and reflection of important values and additional information (Danner, Aarts and Vries, 2008; Verplanken *et al.*, 2008). Mobility research defines such context changes as *key events* (cf. Scheiner, 2007), that can have biographical (e.g. birth of a child, enter a profession) or external triggers such as exogenous interventions (Busch-Geertsema *et al.*, 2016, p. 768). Exogenous interventions that cause context changes can either directly target a specific change in mobility behaviour (e.g. a temporary free public transport ticket) or indirectly bring about such behavioural change through temporary or permanent infrastructure changes (e.g. a closure of a neighbourhood for cars or the introduction of 'pop-up' bike lanes) (Busch-Geertsema *et al.*, 2016, pp. 767 f.). The created window of opportunity can then be leveraged through further attitude- and behaviour-influencing interventions (e.g. feedback, information and communication strategies) to initiate a process of behavioural change towards a more sustainable mobility behaviour (Verplanken *et al.*, 2008; Busch-Geertsema *et al.*, 2016, pp. 767 f.).

2.4 The experimental turn – real-world laboratories and real-world experiments

A popular research approach that investigates societal transition and transformation processes towards sustainable development at the intersection of science and society is that of the *real-world laboratories* (RwLs). RwLs are a combination of transdisciplinary and transformative sustainability research with a focus on innovation, participation and long-term societal learning processes through real-world interventions, the so-called 'real-world experiments' (Schneidewind *et al.*, 2016; Schöpke *et al.*, 2017). RwLs are intended to generate 'actionable' and 'transformative knowledge' about socio-technical systems, social dynamics and processes within societal problem fields and to contribute to their transformation towards sustainability (WBGU, 2011; Schneidewind 2014; Schöpke *et al.*, 2017). Central methodological basis are the real-world experiments, which are designed to develop evidence on solution strategies for sustainability challenges, test acquired knowledge in context-specific application and to foster local social and/or technical innovations (Schöpke *et al.*, 2017). In this way,

RwLs and their experiments contribute to the concrete shaping of change through the development and experimental testing of innovations in the physical-technical and social spheres (WBGU, 2016; Luederitz *et al.*, 2017; Schöpke *et al.*, 2017). In concrete terms, social transition processes such as the transformation of city districts, the introduction of sustainable mobility or energy systems can be better understood and cooperatively shaped.

Cities in the focus

RwLs and the experiments they involve have a strong focus on urban settings (cf. Bulkeley, Castán Broto and Maassen, 2014; Schneidewind, 2014; Schneidewind *et al.* 2016; WBGU, 2016; Bulkeley *et al.*, 2018). The background is the rapidly increasing trend of urbanisation and the associated challenges with regard to climate change and sustainability problems (WBGU, 2016; UN, 2018). Linked to this is the increased awareness of urban authorities and stakeholders for the local and global responsibility of a sustainable transformation of cities as an integral part of the solution to these problems (cf. C40, 2021; Covenant of Mayors, 2021; ICLEI, 2021). Cities themselves become RwLs for their own transformative solutions adapted to local conditions and contexts (WBGU, 2016). At the structural level of the urban context, RwLs can encompass the entire city, city districts or individual households (Schneidewind, 2014). For example, at the household level, new technologies and intervention strategies are being studied in particular (Schneidewind, 2014). Reusswig, Lass and Bock (2020) find the modern city itself as a 'product' of socio-technical experimentation rather than just a spatial 'container' for it.

Physical and social structures of change

Within socio-technical experimentation, a theoretical distinction can be made between changes in physical and social structures, which are, however, strongly intertwined in reality (Luederitz *et al.*, 2017). The change of physical structures concerns the development or transformation of infrastructures, buildings, technologies and

products like f.i. sustainable construction, innovative and smart energy systems and new forms of low-carbon or sustainable mobility (cf. Vergragt and Brown, 2007; Brown and Vergragt, 2008; Canzler *et al.*, 2017). Changes in physical structures may or even need to be accompanied by corresponding changes in institutions, governance and business models as well as individual or collective attitudes, perceptions, decision-making processes, practices, lifestyles and behaviour to effectively achieve the desired and required change. Correspondingly, RwLs and related approaches also study and explore change in the social sphere. Concrete examples of RwLs and experiments for social change and learning are new business models and regulations, changing norms and policies, shifted mobility practices and behaviour as well as energy-saving behaviour and changing consumption patterns (cf. Abrahamse *et al.*, 2007; Davies and Doyle, 2015; Schwartz *et al.*, 2015; Greiff *et al.*, 2016; Canzler *et al.*, 2017; Reusswig, Lass and Bock, 2020).

RwLs as 'opportunity windows' for the mobility transition

In its key recommendation for transformative fields of action with regard to urban transport, the German Advisory Council on Global Change (WBGU, 2016) explicitly calls for overcoming the dominance of MPT in cities. The aim should be cities with good accessibility, with short distances, infrastructure that is pedestrian and biker-friendly, and equipped with attractive and affordable public transport systems. In short, walking, biking and public transport should be at the centre of transport planning for a sustainable transformation of urban transport systems (WBGU, 2016).

In the context of the urban mobility transition, Canzler and Knie (2019) argue for a different kind of urban transport, different transport services and also a change in transport or mobility behaviour. They consider experimental spaces such as RwLs as starting points for a transformation in which “*all participants can voluntarily try out new forms of transport practice without having to commit themselves permanently*” (Canzler and Knie, 2019, p. 29). RwL experiments could thereby become spaces for social innovation, for testing a new multioptional mobility culture under real

conditions, giving upcoming new practices the needed space to unfold. This allows changes to be tested in a transparent and reversible way, so that people can get involved with them. It is important that the changes of the experiments can be experienced in everyday life and that something changes in a very practical way (Canzler and Knie, 2019). According to this understanding of RwLs and their experimental interventions, they involve ‘context changes’ in physical (e.g. urban form and transport infrastructure) or social structures (e.g. individual or collective attitudes, practices and norms) that either way might disrupt individuals’ travel habits (cf. section 2.3.3; Verplanken *et al.*, 2008). This could create ‘windows of opportunity’ for behavioural change towards more sustainable mobility behaviour, practices, routines and habits (cf. Verplanken *et al.*, 2008; Busch-Geertsema *et al.*, 2016, pp. 767 f.).

2.5 The real-world lab experiment KLIB

2.5.1 Project design and implementation

‘Climate Neutral Living in Berlin’ (KLIB) was a research project of the Potsdam Institute for Climate Impact Research (PIK) which took place from 2017 to 2018 in the German capital Berlin as its experimental city lab. The project was funded by the German Federal Ministry for the Environment (BMU) within the context of its National Climate Initiative (NKI) for innovative solutions on climate protection (PIK, 2017; Reusswig, Lass and Bock, 2020).

Research objectives

The central objective of KLIB was “*to find out whether private households could be motivated to reduce their personal carbon footprint in a 1-year real-world experiment, utilising a variety of intervention instruments*” (Reusswig, Lass and Bock, 2020, p. 424). The aim was to identify the extent and opportunities of voluntary action to reduce the carbon footprint under existing living, market and policy conditions and to demonstrate that ambitious climate protection is already possible today (Reusswig, Lass and Bock, 2020; Reusswig *et al.*, 2021). For this purpose, participating households tracked

their consumption behaviour throughout 2018 by using a *carbon tracker* online tool. In addition to the main objective, the scientists intended to find out in which areas of everyday life (i.e. domains of household consumption and activity) and by adopting which strategies the households were successful in reducing emissions. And conversely, what factors and obstacles impede the adoption of reduction strategies in the corresponding domains (Reusswig, Lass and Bock, 2020). Based on other studies and previous projects, the ambition was to reduce CO₂-eq emissions by up to 40 % during one year, depending on the initial situation of the households. The research was divided accordingly into the consumption domains of food, mobility, living or housing and other consumption (Reusswig, Lass and Bock, 2020).

Recruitment

The recruitment of households was conducted via a project website, a press release, newspaper adverts and stakeholder media channels. It was deliberately anticipated that these channels would primarily attract people with an interest in climate policy and personal activism, whose willingness to participate voluntarily (without e.g. monetary incentives) would be the highest (Reusswig, Lass and Bock, 2020). In fact, voluntary participation by one's own motivation can be considered a precondition for the 'real-world' character of the experiment. However, the recruitment process and urban context led to a special sample as Reusswig, Lass and Bock (2020) point out: the recruitment process via the named channels led to a 'self-selection bias' of the sample with participating households with a "*higher-than-average general interest in climate change and carbon footprint reduction*" (Reusswig, Lass and Bock, 2020, p. 429). Correspondingly, the self-selection bias in turn led to a certain 'green bias' of the sample. Moreover, with the designation of Berlin as the setting for the RwL experiment, an 'urban bias' of the sample was present. Both the 'green bias' and the 'urban bias' are of interest for this study with respect to the results and their discussion. The sampling method could be described as a 'random, self-selective sampling'.

In the end, 170 Berlin households completed the baseline survey, 152 converted to active participants from which finally 72 households (47.4 %) tracked their consumption behaviour throughout the observation period of 52 weeks (Reusswig, Lass and Bock, 2020). The carbon footprint results (following section) are based on the data analysis of these 72 households by Reusswig, Lass and Bock (2020). The household size distribution within the sample diverged from the average distribution in Berlin with fewer one-person households and more multi-person households (4+ persons), which were primarily family households with children (Reusswig, Lass and Bock, 2020). An above-average proportion of KLIB households disposed of a middle-income at the time of the survey, whereas lower and higher income households were underrepresented compared to the average income distribution in Berlin (Reusswig, Lass and Bock, 2020). With regard to income, the 'green bias' of the sample is again of interest and it should be noted what Reusswig, Lass and Bock (2020) stress in this context: in fact, attitudinal 'green consumers' often do have higher disposable incomes. Income in turn is a strong driver of both consumption and emissions, in particular related to transport (Kleinhüchelkotten, Neitzke and Moser, 2016; Pichler *et al.*, 2017; Ivanova and Wood, 2020).

Setup

The participating households were scientifically accompanied by the PIK scientists and received professional advice in all relevant domains of household consumption (Reusswig, Lass and Bock, 2020). Furthermore, they were supported by a broad range of project stakeholders along sustainably oriented companies, non-governmental organisations, civil society organisations and initiatives with their portfolio of and expertise on climate-friendly products and services. Care was taken to ensure that all expert advice, products and services offered within the scope of the project are accessible in 'real life' (PIK, 2017b). Indeed, the participating households received neither material or financial incentives nor special technological equipment to support their efforts in reducing their carbon footprints. They had to cope with the existing

infrastructure, market conditions and regulatory legal framework¹¹ (Reusswig, Lass and Bock, 2020). The KLIB project consequently had a quasi-experimental¹² design in terms of research design terminology. To obtain valid results of ‘real-world’ phenomena such as behavioural changes in socio-spatial contexts, a closed, artificial experimental design is not expedient (Sovacool, Axsen and Sorrell, 2018; Reusswig, Lass and Bock, 2020). Accordingly, a quasi-experimental design was chosen for KLIB, with the intention to preserve the socio-spatial contexts of the participants and thus obtaining valid results on the emissions reduction potential of voluntary behaviour change (Reusswig, Lass and Bock, 2020). A portfolio of nine interventions defined the experimental character of the project and was used to motivate and support the participating households to adopt sound reduction strategies and measures (cf. Reusswig, Lass and Bock, 2020).

In the following, only those interventions are presented that are relevant to the objective of the present thesis with respect to the mobility domain of the KLIB project.

Interventions

Baseline survey. The first intervention was also the precondition for active participation. Interested households had to complete the baseline survey for 2017 (as the reference year) that included an annual retrospective assessment of their consumption behaviour for the different domains using a baseline version of the carbon tracker (Reusswig, Lass and Bock, 2020). For the domain of mobility, all trips and distances travelled in 2017 with the individual means of transport or transport mode groups (i.e. private car, bike, carsharing, public transport as well as air travel) had to be assessed retrospectively for the household members combined. The carbon tracker

¹¹ In this context, KLIB differs clearly from other Rwl experiments in which participants are provided with innovative technologies or services to test them or in which new regulatory frameworks are explicitly created for this purpose (Reusswig, Lass and Bock, 2020).

¹² KLIB had a quasi-experimental design as there was no randomised allocation of the sample (participating households), no control group had been set up and it was a deliberate part of the ‘real-world’ design that complete control of all experimental components is neither possible nor wanted (Reusswig, Lass and Bock, 2020).

online tool calculated the according total CO₂-eq emissions in kg per person and household, which were used as reference values – the ‘baseline values’ – for the respective transport modes (Reusswig, Lass and Bock, 2020).

Carbon tracker. The carbon tracker online tool was the core intervention of the KLIB project. It was developed together with the baseline version by the private company KlimAktiv, which also developed and operates the carbon calculator of the Federal Environment Agency (UBA) (cf. UBA, KlimAktiv and ifeu, 2020b). Using this tool, participating households were able to record and track their emissions-related consumption and activities on a weekly basis for each of the relevant domains (food, mobility, living/housing and other consumption). That way, they received direct feedback on the CO₂-eq intensity of their activities and consumption patterns, including their respective impact on the carbon footprint. Weekly reminders were sent via e-mail. The weekly tracked results were compared on the project website with those of other households as well as the German average (Reusswig, Lass and Bock, 2020). The social comparison and carbon footprint benchmarking with other households and the German average should serve to assess one’s own performance and, if necessary, to motivate for more ambitious reduction efforts in the according domains. Furthermore, with regard to the weekly direct feedback of the carbon tracker as well as for the evaluation of the final carbon footprint results, the German average served as the ‘quasi’ control group (Reusswig, Lass and Bock, 2020). A detailed description of the methodological basis and operating principle of the carbon tracker will follow in the methodology section (3.1.2) of this study.

Project website – low-carbon tips (for mobility). On the project website the KLIB scientists compiled a variety of ‘low-carbon tips’ for the respective domains and fields of action. For mobility they emphasised the relevance of the domain with numbers and facts about the still increasing MPT and the strong impact of the private car and air travel on the personal carbon footprint (cf. PIK, 2018). Conversely, they also stressed the leverage effect for emissions reductions that could be achieved by giving up the private car and air travel and switching to alternative CO₂-neutral or low-carbon

means of transport like bike or public transport (cf. PIK, 2018). The tips were formulated in a positive, motivating language that also highlighted the additional benefits for health, environment, better city air and efficiency gains on short trips of e.g. bike vs. car (cf. PIK, 2018). *Table 1* presents an overview on the mobility-related low-carbon tips provided on the project website categorised along the corresponding mode of transport.

Discussion forum and live meetings. The project website also hosted a discussion forum where participants could communicate and exchange views on project-related issues. It thus served as an important peer-to-peer learning and exchange space alongside the live meetings. Live meetings also contributed the dissemination of information, but especially to the community-building among the participants in terms of the social character of the project. For instance, the topic of air travel and its high emissions impact led to vivid discussions about behavioural and technological alternatives (Reusswig, Lass and Bock, 2020; Reusswig *et al.*, 2021).

Stakeholder network – low-carbon products and services (for mobility).

In addition to the low-carbon tips, products and services of the KLIB stakeholder network were offered on the project website for the respective domains. For mobility, a bike rental/sharing provider as well as carsharing provider can be noted. Moreover, a provider of cost-free, environmentally friendly web and telephone conferencing was part of the network to avoid work trips and business travel. For the purpose of emissions compensation, an association that uses donations to delete emissions allowances from the EU Emissions Trading System (EU ETS) was also part of the network. In addition, a foundation and provider for the calculation and compensation of incurred climate-relevant costs of travelling provided its tools and services and established a local citizens' fund for climate protection and sustainable development (PIK, 2017b).

Table 1: Low-carbon mobility tips per mode of transport (own evaluation¹³)

Mode of transport	Low-carbon tips	Related facts and explanations
Private car	- Consider whether you really need your car	- On average, one t CO ₂ savings per year if car is abolished → instead travel by public transport, on foot, by bike/cargo bike or carsharing - Studies show that distances travelled by car are on average less than 5 km → carbon neutral alternatives like bike and on foot are healthier, financially advantageous and faster on short distances (bike, under distance of 5 km)
	- Consider the social impact of car driving as well	- Efficiency gains lead to rebound effects and bigger cars → more public space needed → social problem
Carsharing	- Use carsharing when you can't do without a motorised transport vehicle	- Active carsharing users cause 290 kg less CO ₂ emissions per year
Public transport	- Shift to public transport	- Numerous travel agencies help to research good and affordable rail travel to other European countries
	- Plan trips within Germany and Europe by train (instead of plane)	- A flight from Berlin to Cologne → almost 200 kg of CO ₂ per person, by train → journey only slightly longer, but you save a lot on your carbon footprint
Bike and on foot	- Choose bike or on foot instead of car to do good in many ways	- Improve your climate footprint, strengthen your fitness and promote your health, improve city air quality and reduce noise levels
	- Rely on non-motorised transport as much as possible	- Shifting 2,000 km a year to cycling or walking saves about 440 kg of CO ₂ emissions
	- Use cargo bikes for larger transports	- No need to buy one, borrow it free of charge in your neighbourhood (https://flotte-berlin.de)
Air travel	- Avoid air travel (switch to train instead)	- Ideally each person should only emit 1-2 t of CO ₂ per year, air travel emissions figures speak for themselves: flight to Mallorca - 0.5 t ; [...]; flight to Tenerife - 1.3 t ; [...]; flight to New York - 2.5 t ; flight to Hanoi - 4 t (round trip, one person; Source: atmosfair.de) - Emissions from long-distance flights with altitudes above 10 km → 3 times the effect of ground-level emissions → water vapour and other emissions influence cloud formation with strong negative effects
	- Think of dream holiday destinations in the closer vicinity (reachable by train)	- It is above all the flights that have a significant impact on your carbon footprint → think of destinations in Germany or European countries reachable by train

According to Reusswig, Lass and Bock (2020), the described interventions relevant for the domain of mobility were attributed to the 'innovation' and 'social' (innovative) character of the experiment. They emphasised that the innovative character not only

¹³ Own evaluation of the tips and advice for the domain of mobility on the official KLIB website (cf. PIK, 2018). The authors are responsible for the correctness of the information provided. Sources are available on the website (cf. PIK, 2018).

relied on innovative products and services, but also on innovative practices. This is especially valid for the domain of mobility where interventions targeted behavioural changes in modal choice and transport demand. Concretely, interventions like the carbon tracker and low-carbon mobility tips focused on informing about the carbon impact of mobility behaviour as well as motivating and encouraging the households to adopt modal shift or modal avoidance strategies and measures (cf. *Table 1*; PIK, 2018).

2.5.2 Present results of KLIB

In the following, a brief overview of the present results of the KLIB project is given, based on the first analysis of the 72 households by Reusswig, Lass and Bock (2020) with a focus on the mobility-specific context of this study.

On average, the KLIB households started with a carbon footprint of 8754 kg CO₂-eq for 2017 which was already 24.6 % less than the German average of approximately 11630 kg CO₂-eq per capita. However, the share of mobility-related emissions with 2190 kg CO₂-eq was almost the same as the according mobility-related emissions of the German average (2180 kg CO₂-eq). During the one-year real lab phase, KLIB households managed to reduce their average carbon footprint to 7780 kg CO₂-eq per capita in 2018, which equates to 11.1 % less emissions compared to the baseline and 33 % less than the German average (Reusswig, Lass and Bock, 2020). For the domain of mobility, KLIB emissions accounted 1836 kg CO₂-eq per capita in 2018, which corresponds for 23.5 % of the total average carbon footprint in 2018 (Reusswig, Lass and Bock, 2020). However, Reusswig, Lass and Bock (2020) found high differences in the CO₂-eq emissions reductions among the participating households: “*while some households managed to reduce by about 40 %, others reported increases by up to 30 %*” (Reusswig, Lass and Bock, 2020, p. 429). The found differences in emissions reductions or even increases give reasons to have a closer look at the causes for these differences, which is part of the objectives of this study.

Highest average emissions reductions were achieved in the domains of mobility (16.2 %) and other consumption (13.4 %), while the domains of living (7.2 %) and food (7 %) showed minor reductions (Reusswig, Lass and Bock, 2020). Differentiating the domain of mobility in ground mobility and air travel revealed that KLIB households reduced emissions successful in ground mobility (38.7 %), but only little in air travel (5.3 %). In fact, air travel was the only domain in which the KLIB households showed clearly higher baseline (1404 kg CO₂-eq) and KLIB (1331 kg CO₂-eq) per capita emissions balances than the German average (580 kg CO₂-eq). In addition, a first detailed analysis of the households with an increased carbon footprint showed that for the majority, air travel was the main reason for emissions increases (Reusswig, Lass and Bock, 2020).

IGES, Aalto University and D-mat ltd. (2019) calculated that a reduction of the carbon footprint by 8–12 % per year would be necessary to achieve the Paris Agreement target of limiting global warming to 1.5 °C. Following these findings, Reusswig, Lass and Bock (2020) conclude that the KLIB households met the Paris Agreement target in 2018 with an average annual per capita reduction in CO₂-eq emissions of 11.1 %. In this sense the KLIB project indeed showed that ambitious climate protection is possible under existing living and market conditions and regulatory framework.

However, despite the ‘green’ and ‘urban bias’, the KLIB sample comprised a heterogeneous mix of different household types with, in turn, individually different living situations, diverse lifestyles and preconditions for action. As introduced in section 2.2.4, other studies showed that per capita carbon footprints are decisively influenced by characteristics concerning the living situation of households like household size, age structure, income, the available means of transport as well as related decisions, social practices and routines (cf. Jones and Kammen, 2014; Greiff *et al.*, 2016; Kleinhüchelkotten, Neitzke and Moser, 2016; Miehe *et al.*, 2016; Ivanova *et al.*, 2018; Dubois *et al.*, 2019). In this respect it is conclusive to take a more differentiated look at the KLIB households along relevant household characteristics and question whether, for example, family households were able to save as much emissions on

average as single households or couple households? Or what differences in emissions reductions and carbon footprints can be identified along the car equipment of the households? This is particularly interesting for the domain of mobility, as this is where the highest average reductions were achieved.

3 Research design and methodology

In order to obtain an appropriate analytical access to the KLIB households mobility data set, a transport sociologically grounded, qualitative approach of *empirically based type formation* was applied. The type formation's objective was to structure and organise the households (examination elements) and their according mobility data along relevant household characteristics influencing the mobility behaviour and the associated CO₂-eq emissions. Subsequently, a type-based, descriptive statistical data analysis was conducted to evaluate the mobility data set of the households concerning mobility patterns and associated emissions. Accordingly, the research design follows a mixed methods approach, using qualitative (type formation) and quantitative (descriptive statistical data analysis) methods of evaluation.

The data analysis was based on secondary data collected during the KLIB project through the *carbon tracker* intervention tool and individual data inputs of the participating households. The data basis was thus taken over from the researchers of the PIK project team. Therefore, the data collection will be described retrospectively in the context of the KLIB project, with a detailed focus on the carbon tracker, its methodological basis and calculation principle as well as the mode of input and a specification of the output data set as the basis for this study. Leading up to the actual data analysis, a detailed data preparation of the households' mobility data set was carried out first. This included data aggregation, data cleansing and correction, which was followed by the central qualitative method of type formation. The mobility and associated emissions data of the types formed were finally analysed individually per type using descriptive statistical methods and calculations.

3.1 Data collection within KLIB

The data collection relevant for this study is confined to the recruitment of the KLIB households (sampling) and the actual recording or tracking of mobility data by the households through the carbon tracker intervention tool.

3.1.1 Sampling – recruitment of households

The sampling method for the recruitment of households can be described as ‘random, self-selective sampling’. The recruitment was conducted through the project website, a press release and stakeholder media channels (Reusswig, Lass and Bock, 2020). The sampling was ‘random’ as theoretically everyone could participate. Yet, it was also ‘self-selective’, as it was clear from the outset that the project would predominantly attract people with a higher interest in climate change, personal activism and carbon footprint reduction. The self-selective sampling in turn also led to a ‘green bias’ of the sample. In this respect and likewise considering the ‘urban bias’ related to the urban setting of the project, it is evident that the sample is not representative (cf. section 2.5.1, *Recruitment*). This is of relevance for the overall results of the project as well as the results of this study which will be discussed accordingly later in this context.

3.1.2 The carbon tracker

The *carbon tracker* presents the central tool of data collection for this study. Each KLIB household had its own user account with a customisable user profile. The online tool enabled the households to record their consumption and all emissions-relevant activities along the according domains of living, mobility, food and other consumption. As a result, they received direct visual feedback on the associated CO₂-eq emissions, both broken down by individual activity or consumption and accumulated along the respective domain categories. Hence, the households could individually track the impact of their actions on the carbon footprint.

Methodological basis and calculation principle

The carbon tracker online tool for the weekly tracking as well as the baseline version were developed and operated by the private company KlimAktiv which has also developed and operates the UBA Carbon Calculator (cf. http://www.uba.co2-rechner.de/de_DE/) in cooperation with the Institute for Energy and Environmental Research Heidelberg (ifeu) (cf. UBA, KlimAktiv and ifeu, 2020b). Hence, both tools are

based on the same methodology, data basis and operating principle. KLIB emissions balances are thus comparable with the German average per capita emissions balances provided by the UBA for the corresponding domains or sectors. The methodological basis for the calculation of individual CO₂-eq balances was provided by the study 'CO₂ balance of the citizen' (cf. Schächtele and Hertle, 2007) within a research project commissioned by the UBA. The objective was to provide a standardised, consistent and transparent online tool for calculating CO₂-eq emissions for all relevant domains or sectors, covering broad areas of sector-specific applications, activities and emissions sources (Schächtele and Hertle, 2007).

The calculation principle is based on the average emissions values in Germany per sector related to the activities of consumers living in Germany. Thus, the calculation basis follows a consumption-based *carbon footprint* approach instead of the territorial principle in line with the national GHG inventory reporting of the United Nations Framework Convention on Climate Change and the IPCC (cf. IPCC, 2019; UBA, 2021b). Under the territorial principle, GHG emissions emitted in Germany are apportioned to the number of citizens in Germany, but neither emissions related to imported consumer goods are added nor those of exported goods are subtracted (Schächtele and Hertle, 2007; UBA, 2021b). The consumption-based approach considers all CO₂-eq emissions that a consumer in Germany actually or on average cause through his consumption behaviour and activities, including direct and indirect or embedded emissions from products and services (Schächtele and Hertle, 2007). Accordingly, the consumption-based approach is the appropriate one to correctly quantify the impact of lifestyles, behaviour and consumption patterns of individuals or households as well as to accurately measure the effects of behavioral changes on emissions balances (cf. section 2.2.2).

In addition to CO₂, the carbon tracker considers the GHGs methane (CH₄), nitrous oxide (N₂O) and *non-CO₂ effects* of air travel (cf. 2.1.2; *non-CO₂ effects*) in their corresponding climate impact compared to CO₂ as reference (cf. section 3.3.2). For better

comparability, their Global Warming Potential¹⁴ (GWP) is expressed in *CO₂-equivalent emissions* (Schächtele and Hertle, 2007). With respect to a cross-sectoral comparison of the consumption-based average per capita emissions it is reasonable to work with *CO₂-equivalent emissions*.

The emissions data used in the carbon tracker's calculation model are based on the Transport Emission Model (TREMOD) developed by ifeu, the environmental-economic accounts of the German Federal Statistical Office (StBA), the publications of the 'AG Energiebilanzen' (AGEB) as well as calculations by ifeu and KlimAktiv (Schächtele and Hertle, 2007; UBA, KlimAktiv and ifeu, 2020a). Based on the emissions data and influencing calculation factors, the direct and indirect *CO₂-eq* emissions per sector and subcategory are calculated for the average German citizen. These values are finally scaled with the user's input for the respective domains to calculate the individual *CO₂-eq* balance for the according domain or subcategory (UBA, KlimAktiv and ifeu, 2020a). *CO₂-eq* influencing factors, comparative values and the framework conditions change over time. Accordingly, the emissions data and influencing factors are regularly updated along the latest sectoral inventories and scientific findings and integrated into the calculation model (UBA, KlimAktiv and ifeu, 2020a). Thus, the average carbon footprint values for Germany of the UBA also change regularly. In this connection, it should be emphasised that the German average values for the domain of mobility presented in this study always refer to the UBA values of 2018, to which the findings of Reusswig, Lass and Bock (2020) also reference.

The calculation of *CO₂-eq* emissions values in the transport sector is generally based on the consumption or combustion of fossil fuels within passenger transport and the emissions of the upstream fuel production processes (Schächtele and Hertle, 2007). Within the subcategory MPT, the individual share of emissions per person and trip is

¹⁴ The Global Warming Potential (GWP) is an index measuring the radiative forcing (in W/m^2) of an emitted amount of GHG over a chosen period of time (usually 100 years) relative to the reference substance CO_2 (IPCC, 2014, p. 124). The radiative forcing of CO_2 correspondingly equals the factor 1. For example, the radiative forcing of 1 kg methane (CH_4) over a period of 100 years is 28 times greater than that of 1 kg CO_2 (1 kg CH_4 = 28 kg *CO₂-eq*). For nitrous oxide (N_2O), the factor is 265 (1 kg N_2O = 265 kg *CO₂-eq*).

calculated by dividing the total emissions of the distance travelled by the number of passengers. The same applies to the carsharing mode (UBA and KlimAktiv, 2020a). For public transport, emissions are calculated using a statistically grounded average value of the transport mode mix (UBA and KlimAktiv, 2020a). Emissions of electric mobility are based on the type of electric energy used for charging (renewable vs. conventional electricity mix). Biking or covering distances on foot are consequently carbon neutral and can be considered as emissions avoidance (UBA and KlimAktiv, 2020a). For air travel, CO₂-eq emissions are calculated from the combustion of fossil fuels and their upstream production processes, same as in ground mobility (UBA and KlimAktiv, 2020c). On top of this, however, there are the non-CO₂ effects (cf. 2.1.2; *non-CO2 effects*) which have an additional radiative forcing ('climate impact') (Schächtele and Hertle, 2007; Lee *et al.*, 2021). According to current knowledge, these non-CO₂ effects multiply the radiative forcing of CO₂ emissions from air travel by a factor of approximately 2–3 (Schächtele and Hertle, 2007; UBA and KlimAktiv, 2020c; Lee *et al.*, 2021). This additional radiative forcing of air travel is considered in the calculation principle of the carbon tracker (UBA and KlimAktiv, 2020c).

Input – tracking of mobility

The online tool was structured according to the emissions-relevant domains and sub-categories, each with separate input windows. The domain specific input windows were again subdivided in individual input panels with diverse selection and input options specified to the requirements of the respective category. The mobility category was subdivided by three input tabs: the first tab served to record the available motorised means of transport along details on the vehicle class and age, fuel type and average fuel consumption. A second tab was designated for the actual input and recording of trips and journeys in the domain of ground mobility. For the recording of each distance travelled, whether commuting or travelling, the participants had to select the means of transport, enter the distance (there and back) and the number of times they made the trip per week ('frequency factor') as well as enter a description or name. In addition to the means of transport the participants added themselves,

there were various other mobility options to choose from. This included carsharing, long-distance train transport (German railways or other long-distance train transport¹⁵), short-distance train transport, local public transport, coach as well as partly motorised and non-motorised means of transport such as e-bike, bike and on foot. The third tab was designated for recording air travel. It was required to enter the departure and destination airports as well as possible stopovers, whether it was a one-way or return flight, the chosen flight class (economy, business, first class), the number of passengers and the number of flights (if recurring).

Based on the input parameters (e.g. means of transport, distance travelled and 'frequency factor' of trip), the carbon tracker calculated the associated emissions of the trip or journey in kg CO₂-eq and added them to the emissions balances in the according category and domain of the carbon footprint, in this case mobility. The overall footprint results (in t CO₂-eq) were presented in graphs per domain category and as a whole, compared with the other participating households and the German average carbon footprint (Reusswig, Lass and Bock, 2020). This allowed households to constantly benchmark their own performance in the different domains or categories and, in theory, to adjust their behaviour and consumption patterns if required or desired.

Baseline survey version

The *baseline survey version* of the carbon tracker was based on the same input mask and principle with two decisive differences that are particularly relevant for the mobility domain and its results. Firstly, instead of the 'detailed entry variant' (like for the weekly version), a 'lump-sum variant' was used for the baseline survey. In this entry variant, ground mobility was only differentiated along the self-added vehicles and the modalities bike, carsharing and public transport. By entering a total number

¹⁵ The differentiation of long-distance train transport is important under the aspect that, according to its own statements, German Railways has been using 100 % renewable energies for long-distance passenger transport since the beginning of 2018 (DB, 2021). Therefore, journeys with it are significantly less CO₂-eq intensive compared to other domestic and foreign railway companies (other long distance train transport), which was considered in the calculation basis of the carbon tracker (cf. UBA and KlimAktiv, 2020a).

of kilometres per mode of transport for the entire year 2017, the corresponding CO₂-eq emissions were calculated. Thus, secondly, the complete mobility patterns of each person in a household had to be estimated retrospectively for the according modes of transport in 2017. This is a critically questionable approach to the collection of mobility data (Knie, 2016, pp. 37 f.). However, it is a characteristic data collection problem of transport research in general, which is also shared by the large comparative mobility studies in Germany ‘Mobility in Cities’ (SrV) (cf. Gerike *et al.*, 2020) and ‘Mobility in Germany’ (MID) (cf. Eggs *et al.*, 2018; Nobis and Kuhnimhof, 2018). It is generally very difficult to depict mobility behaviour retrospectively in an empirically valid way (Knie, 2016, pp. 37 f.; Sammer, 2016, pp. 703 ff.). This data collection problem and its impact on the validity and reliability of the data will be discussed in the methodological limitations of this study (cf. section 5.3.1).

Output – mobility in data

The data output of the whole sample for the domain of mobility relevant for this study’s analysis was composed of an extensive data set within a Microsoft Excel spreadsheet file with data sheets on ground mobility and air travel. However, it was decided that this study would only focus on the 72 households that Reusswig, Lass and Bock (2020) analysed in more detail, or even less than this after data cleansing considering the mobility tracking requirements. The following will briefly describe the data output sheets relevant for this study’s analysis.

The data sheet for ground mobility comprised the mobility data for the baseline year 2017 (‘kw’ = 0) and the 52 weeks of 2018 from each of the 72 households in sorted, sequential order along the user identification (ID) numbers. Consequently, the first five columns always contained the user ID (‘user_id’), followed by the calendar week (‘kw’), the calculation mode (‘calc_mode’; whether household or single person), the number of persons or household size (‘persons’) and the summed emissions for the respective calendar week (‘emissions’). This was followed by a column in which participants could enter their reduction intentions for the upcoming week(s)

('reduction_projection_text', e.g. "*more cycling*"), which was generally rarely used. The next column contained all the specified vehicles (motorised means of transport) and associated information such as vehicle class, fuel type and fuel consumption ('cars'). The following four columns provided the aggregated data on driving or transport performance for the baseline year 2017, broken down into the four modalities private car, car sharing, bike and public transport. The baseline transport performances were always shown in the first row of each household under the designation calendar week zero ('kw' = 0). In the following columns, the actual mobility data were shown in the form of individual trips or trip blocks for each of the 52 calendar weeks in the same output pattern: each individual trip or block of trips consisted of six interconnected columns containing the proportional emissions (e.g. 'emission_1'), the name or description of the trip (e.g. 'name_1'), the mode of transport (e.g. 'vehicle_1'), whether scheduled or unscheduled (e.g. 'period_1'), the distance travelled (e.g. 'road_performance_1') and the 'frequency factor' of the trip (e.g. 'days_1'). Accordingly, each recorded trip or trip block per calendar week was presented consecutively in correspondingly numbered column units ('kw trip IDs': e.g. 'x_1'). The maximum number of trips or trip blocks recorded by a household per week were 15 entries. In general, emissions values were expressed in *kg CO₂-equivalent (CO₂-eq) emissions*, driving or transport performances in km respectively *passenger-kilometres (p-km)* (defined in section 3.3.2).

The data output sheet for air travel was structured similarly to that for ground mobility. The first five columns matched. This was followed by the data on the individual flights, similar to the ground mobility trips. The variables recorded for each flight comprised 12 columns, including the associated emissions (e.g. 'emissions_1'), the airport code (e.g. 'start_iata_1') of departure and the name of the city (e.g. 'start_city_1'), the same for possible stopovers and the destination airport. This was followed by the single distance (e.g. 'simple_distance_1') of the flight, the flight class (e.g. 'flight_class_1'), whether it was a return or single flight (e.g. 'flight_mode_1'), the number of passengers (e.g. 'passengers_amount_1') and the number of flights (e.g. 'flight_amount_1').

Tracking performance

The individual way of entering data within ground mobility differed in parts greatly among the households. Some households entered their mobility data in a well-structured and clear form according to the modes of transport used per week and distinguished between recurring everyday mobility, mostly recorded in trip blocks, and special individual trips and journeys. Others entered each individual trip chronologically according to the weekly schedule, in the exact order in which they occurred. This also created a certain pattern in the data output sheet, but a less structured and more varied one in terms of modes and respective transport performances. Still other households entered data relatively randomly without a clear pattern, sometimes according to modes of transport, sometimes chronologically with partial blank entries. A few households showed relatively large data gaps.

However, in order to determine the modal split, the transport performance by mode of transport and the associated CO₂-eq emissions per household, a clear evaluation of the data was needed, structured by mode of transport. This was a challenge because the heterogeneity of input variants meant that no programmed 'readout algorithms' could be used for data analysis. Thus, the entire data set of the 72 households had to be broken down individually week by week and trip by trip and condensed into a new data sheet structured and ordered according to means of transport, transport performance and emissions. Accordingly, a data aggregation and, with regard to the few households with larger data gaps, an additional data cleansing was conducted. This is described in the following section.

The data on recorded flights within the 'air travel data output sheet' was overall much clearer and more structured. This was probably largely due to the fact that it is not a matter of everyday mobility and therefore the input parameters could only be entered in one clear and unambiguous form. The carbon tracker then suggested the corresponding flight route and calculated the according variables after the users' confirmation.

3.2 Data preparation

The data preparation as a whole was the precondition for the actual data analysis, in partial respects it was already a component of it. Data preparation consisted of the ordering and condensation of the mobility data (data aggregation), a data cleansing and correction as well as the central method of type formation. All practical steps of the data preparation were conducted within the spreadsheet and data analysis programme Microsoft Excel (Version: Microsoft® Excel® for Microsoft 365 MSO (16.0.13127.21210) 64-bit).

3.2.1 Data aggregation

The objective of data aggregation was to clearly organise the households' mobility data set for the following analyses according to the modes of transport and subordinate variables (transport performance and emissions). Moreover, a condensation to the annual scale should serve a concise overview and improved comparability of the households.

In the first step, the data of ground mobility was structured and condensed according to modes of transport on a still weekly scale. For this purpose, a new spreadsheet file was created that took over the first five columns ('user_id', 'kw', 'calc_mode', 'persons', 'emissions') of the data output sheet of the 72 households. A 'total emissions control column' and one for 'total transport performance' were added. In the following, all means of transport were listed in separate columns, each subdivided according to the variables transport performance and corresponding emissions (e.g. 'emissions_carsharing', 'performance_carsharing'). The values of the data output sheet on the individual trips and trip blocks were now totaled week by week per household and means of transport (within the according variables) in the new spreadsheet file. 'Frequency factors' of trip blocks were factored in. The calculations were carried out twice per household to exclude errors, whereby the 'emissions control column' served as an additional check and correctness assurance. This step was conducted meticulously and also included the data cleaning and correction, which will be addressed in the next section (cf. section 3.2.2).

In the second step of data aggregation, all variables (in columns) of the households (in rows) were condensed on an annual scale and organised in another comprehensive data sheet. In this way, only one data row per household containing all corresponding values of the variables was necessary. The first two columns still contained the user ID and household size (for later per capita calculations) as constants. In the following columns, a distinction was made between the main variables of ground mobility (precise designation: 'baseline_total_emissions_ground', 'KLIB_total_emissions_ground', 'ground_emissions_difference', 'baseline_total_performance', 'KLIB_total_performance', 'total_performance_difference') and the variables related to the individual means of transport (e.g. 'emissions_mpt', 'baseline_performance_mpt', 'performance_mpt' etc.).

In line with the major mobility studies in Germany MID and SrV, the means of local and long-distance public transport (e.g. long-distance train, long-distance bus, local train, suburban train, underground, tram, local bus, etc.) were combined under the mode group of 'public transport' to achieve a concise overview and better comparability among the modes of transport (cf. Nobis and Kuhnimhof, 2018; Gerike *et al.*, 2020). Accordingly, for ground mobility an analytical distinction was made between the MPT, effectively represented by the private car¹⁶, carsharing, bike, on foot and public transport.

The main variables of air travel (precise designation: 'baseline_emissions_air', 'KLIB_emissions_air', 'air_emissions_difference', 'baseline_distance_air', 'KLIB_distance_air', 'baseline_count_oneway', 'KLIB_count_oneway') were listed separately in the following columns. The values of air travel were fed from the corresponding separate data output sheet and equally condensed to the annual scale.

¹⁶ The *motorised private transport* (MPT) in this study's sample is fully represented by the 'private car'. Two motorbikes were recorded, however not used during the tracking period. This circumstance reflects the proportional dominance of cars within the MPT in Germany (Nobis and Kuhnimhof, 2018).

3.2.2 Data cleansing and correction

The KLIB project's analysis by Reusswig, Lass and Bock (2020) focused on the 72 households that tracked their activities and consumption in the different domains. However, as already indicated (cf. section 3.1.2, *Tracking performance*), the tracking of mobility was not constant for some households and clearly insufficient in a few cases due to large data gaps. Yet, continuous tracking explicitly in the mobility domain is important to obtain a comparable data set for each household and thus an realistic approximation of the transport performance per mode and the according CO₂-eq emissions. To address this problem, a criteria guided data cleansing was applied informed by data analysis literature (cf. Hair *et al.*, 2014), which eventually led to the exclusion of nine households from the detailed evaluation. Minor definite input errors were corrected through imputation. In the following, the exclusion criteria of data cleansing will be described and reasoned. Furthermore, two examples are presented: one demonstrating a typical recurring input error and explaining its correction by the imputation procedure, and another one justifying a specific case exclusion. For a detailed overview of all corrected input errors, see *Table 3* at appendix A (cf. *8 Appendix A*).

Exclusion criteria for data analysis

First, the extent of missing data on individual cases (the households) or individual variables that is small enough not to affect the results had to be assessed. The literature on data analysis suggests that missing data below 10 % for an individual case can generally be ignored, more than 30 % should though be resolved through either deletion of the case or imputation of the data (Hair *et al.*, 2014, pp. 45 f.). Furthermore, any non-random patterns in the data, such as the concentration of missing data in a particular position or context, should be identified. However, there are no fixed guidelines on the necessary degree for an exclusion, therefore any decision should be based on both empirical and theoretical considerations (Hair *et al.*, 2014, pp. 45 f.).

Since data entry in the context of this study was weekly, a continuous data input or recording over 52 calendar weeks corresponds to a complete data set of a household (individual case). Thus, more than 15 weeks of missing tracking records correspond to more than approximately 30 % of missing data. The first exclusion criteria was set accordingly and excluded households with more than 15 weeks of missing data from the detailed evaluation. The second exclusion criteria focused on non-random patterns and contiguous data gaps and was furthermore always subject to a theoretical assessment of the relationships. If more than 5 (= approximately 10 %) consecutive calendar weeks were missing in the data tracking, affected households were also excluded from the detailed evaluation. The application of both criteria led to the exclusion of six households (user ID 73, 76, 132, 163, 166, 179). For most of them, both criteria were true, two households did not record any mobility data at all (user ID 73 and 76). Three further households were excluded due to serious input errors, questionable extreme outliers in individual variables and theoretical considerations in relation to other correlated variables (user ID 37, 77, 100).

Examples for data correction and case exclusion

It should be noted that questionable entries for individual trips or journeys were only corrected if it was unambiguously evident that an input error had occurred. Evident input errors and associated values were corrected by imputation¹⁷, i.e. by scaling or recalculating the wrong values based on valid values within a similar relationship from other cases (trips or households) in the sample (cf. Hair *et al.*, 2014, p. 48).

Example 1 – data correction. The household with the user ID 54 recorded several long-distance journeys with the same distance travelled (1200 km, there and back) and destination (Cologne), specified in the description of the journey. German railways

¹⁷ Hair *et al.* 2014 define imputation as “the process of estimating the missing value based on valid values of other variables and/or cases in the sample. The objective is to employ known relationships that can be identified in the valid values of the sample to assist in estimating the missing values.”. In fact, incorrect values could be scaled or recalculated (instead of estimated) due to consistent correlations with valid values from other households, e.g. same mode of transport with identical or scalable distance travelled.

(DB, 'long_distance_green') was the selected mode of transport for most of them. However, for four (calendar week 13, twice in 47 and 48) of these long-distance journeys, local public transport ('oepnv') was mistakenly selected. This is obviously an input error as a journey of 1200 km from Berlin to Cologne and back is simply not offered nor possible by means of local public transport, since their services are limited to the respective town or region. Apart from that fact, the journey had previously been made several times with the German railways. Furthermore, within the carbon tracker input mask, 'oepnv' is the default selection for ground mobility trips, which suggests that these were cases of carelessness during the input. Due to the input errors, the actual emissions were increased by 303.94 g CO₂-eq in total. The emissions values were corrected downwards accordingly by imputation from valid values of an identical journey/trip.

Similar input errors as in the case of ID 54 were the most frequent cases of wrong values and also occurred in ID 28, 34, 44, 58, 85, 92, 110 and 153, always in connection with the wrong or default selection of the mode 'oepnv'.

Example 2 – case exclusion. The household 77 was excluded from the data evaluation since wrong information was specified about the private car, which was used frequently. It was indicated as a 'fully battery electric vehicle' (BEV), but in fact the model was only available as a 'hybrid electric vehicle' (HEV). The differences in CO₂-eq emissions in road performance between these vehicle types is considerable. This is because HEVs are on average predominantly powered by the internal combustion engine, as real-world data shows (Plötz, Funke and Jochem, 2020). The carbon tracker's calculation model considered this through different emissions factors for the vehicle types (UBA and KlimAktiv, 2020b). Accordingly, all emissions related to this households' private car driving or transport performance were miscalculated and overall clearly too low. Due to the frequent use of the car, the data was therefore inadequate and would have distorted the overall results.

Data cleansing and correction should improve the reliability of the data basis as a whole as well as the comparability of the individual cases and correspondingly also

their type aggregates. Through the type formation described below and subsequent methods of descriptive statistics, the data basis was to be further improved by averaging the variables in order to reduce the influence of individual questionable data records on the results.

3.2.3 Type formation of mobility-related household types

Type formation is a 'grouping process' in which empirical cases are sorted and united into groups along one or more characteristics and the respective combination of the characteristics' expressions (cf. Kluge 2000; Schmidt-Hertha and Tippelt, 2011). The term 'type' is used to describe the formed subgroups of cases with the same particular arrangement of characteristics and concurring characteristics' expressions. The grouping principle is to gain a high level of homogeneity within a type (*internal homogeneity*) and as much heterogeneity as possible between the different types (*external heterogeneity*) (Kluge, 2000). In doing so, it is important that there is not only an *empirical regularity* (causal adequacy) between the individual characteristics' expressions among the types, but also a *contextual sense* (sense adequacy) (Kluge, 2000). Correspondingly, each typology is based on a 'space of characteristics' which results through the combination of the selected characteristics or rather their comparison dimensions along the characteristics' expressions (Kluge, 2000).

Type formation is a reasonable method when extensive explorative data material, e.g. from complex social realities and contexts, is to be structured and ordered. Thereby, it has the ambition to capture supra-individual patterns while preserving the originality of individual cases and thus combining theory with empiricism (Haas and Scheibelhofer, 1998). A typology helps to gain insights about recurring social structures, processes, and action patterns within empirical reality of individual cases. Furthermore, through the analysis and interpretation of the former, typologies may serve the acquisition of action relevant knowledge, the development of action plans and evaluation of strategies (Schmidt-Hertha and Tippelt, 2011). In this sense type formation is a strategy of information reduction with simultaneous knowledge gain (Schmidt-Hertha and Tippelt, 2011).

In line with the explanations from section 2.2.4 (relevance of the *household living situation* and its socio-demographic characteristics), it is conclusive to structure and organise the different KLIB households more precisely according to relevant household characteristics. Correspondingly, this study follows the insights of transport research: socio-demographic factors describing the household organisation and living situation like household size (number of persons per household), household structure (age and gender of the persons, children in the household, household type: e.g. single, couple, family etc.), household income as well as the available means of transport are robust characteristics to analyse mobility behaviour on the household level (cf. Scheiner, 2016, pp. 691 ff.; Nobis and Kuhnimhof, 2018; Gerike *et al.*, 2020). These characteristics are important factors influencing transport demand and modal choice which in turn are determinants of passenger transport related CO₂-eq emissions (cf. Hunecke *et al.*, 2008; Kleinhüchelkotten, Neitzke and Moser, 2016; Scheiner, 2016, pp. 684 f., 691 ff.). Hence, developing types along characteristics that shape household mobility behaviour and thereby influence the carbon footprint could reveal a more nuanced picture with respect to pattern recognition. It may provide insights to what extent each type reduced emissions in average and how these reductions were achieved in terms of the according mobility patterns, i.e. transport demand and modal choice.

Consequentially, a mobility-related household typology was developed, based on the insights of transport research on relevant characteristics and limited by the availability of collected KLIB household data on the respective characteristics. Thus, also due to the small sample size of 63 remaining households after the data cleansing, a qualitative approach of type formation was chosen. The process of type formation followed the step model of *empirically based type formation* after Kluge (2000). The type formation process after Kluge (2000) differentiates four evaluation steps, starting with (1) the development of comparison dimensions by the selection of relevant characteristics, followed by (2) the grouping of cases and analysis of empirical regularity, (3) the analysis of contextual sense and type formation and finally (4) the characterisation of the types formed. The advantage of the step model of empirically based type

formation is its openness and flexibility. Each evaluation step can be realised through a portfolio of different evaluation methods and techniques. It allows for each study and quality of data material to combine the appropriate and most efficient evaluation methods in order to reach the respective evaluation steps and central objectives of type formation (Kluge, 2000). The following will explain in more detail how the mobility-related household typology was developed following the step model of empirically based type formation after Kluge (2000).

(1) Development of comparison dimensions by selection of characteristics

The qualitative selection of relevant characteristics for the analysis of mobility behaviour was on the one hand guided by the insights of transport research (see above) as well as the two large-scale studies on mobility in Germany, SrV (Gerike *et al.*, 2020) and MID (Eggs *et al.*, 2018; Nobis and Kuhnimhof, 2018), which likewise use a mobility-related household typology. On the other hand, the characteristics' selection process was limited by the available KLIB data gathered during the baseline survey among the participating households. In line with the studies mentioned, the KLIB project's baseline survey collected, among others, data on mobility- and household-relevant characteristics like the *household size* (number of persons living in the household), the *household income* (equivalised disposable income), the *available means of transport* and whether *children live in the household*. It though missed to inquire for a comprehensive reproduction of the age structure and gender of the people living in the participating households. The household and mobility-relevant survey characteristics listed first, for which data were available, set the basis for the type formation process.

(2–3) Grouping of cases, analysis of empirical regularity, analysis of contextual sense and type formation

Within passenger transport, the MPT, primarily represented by private cars, is the main driver of CO₂-eq emissions in ground passenger transport (cf. section 2.1.2; Schelewsky, Follmer and Dickmann, 2020; Allekotte *et al.*, 2021). Moreover, car

ownership is a significant carbon lock-in (cf. section 2.2.4, *carbon lock-in of car ownership*; Ivanova *et al.*, 2018). Correspondingly, there is an undisputed consensus within transport research on the relevance of MPT for CO₂-eq emissions reductions in passenger transport (cf. Bongardt *et al.*, 2013, pp. 46 ff.; Foletta and Henderson, 2016, pp. 1 ff.; ITF, 2017; Canzler *et al.*, 2018, pp. 23 ff.; Ruhrort, 2019, pp. 28 ff., 33 f.). Against this background, it is conclusive to define the MPT, effectively represented by *car ownership*, as the most relevant mobility characteristic of households with regard to emissions within this study's typology. The inclusion of the other available characteristics (*household size*, *household income*, *children living in the household*) along their respective characteristics' expressions, created the 'space of characteristics' (cf. Kluge, 1999) in form of a characteristic matrix – practically this was done within an Excel spreadsheet: each characteristic was represented by the existing characteristics' expressions and values (e.g. for household size: one person, two persons etc.; for car ownership: yes, no), combined in a characteristic matrix. The assignment of the 'examination elements', i.e. the households, fitting a certain combination of characteristics revealed the theoretically possible types. However, the sample was found to be too broadly spread. Two households representing one type is insufficient in terms of empirical regularity (cf. Kluge, 1999) and also statistically not valid with respect to the subsequent analysis methods of descriptive statistics. For this reason, a reduction of the space of characteristics was necessary. *Household income*, the characteristic with the most expressions, was therefore neglected in order to achieve sufficient empirical regularity between the types.

Car ownership split the KLIB sample in two main groups of relatively equal sizes. The two remaining socio-demographic household characteristics, *household size* and *children living in the household*, were combined into the *household type* in methodological (cf. Kluge, 2000) and empirical accordance of social science research as well as with respect to their contextual sense and empirical correlation within the KLIB sample. Accordingly, a distinction was made between three household types – single

household, couple household and family household¹⁸ – which in turn subdivided the main groups (households with car and households without car) respectively.

(4) Characterisation of the types

Finally, six mobility-related household types were formed, considering sufficient empirical regularity (cf. *Table 2*) and contextual sense: ‘single with car’ (SWC), ‘single no car’ (SNC), ‘couple with car’ (CWC), ‘couple no car’ (CNC), ‘family with car’ (FWC), ‘family no car’ (FNC). The household types without a car are termed ‘x no car’ instead of ‘x without car’ for a clearer distinction of the abbreviations which will be used accordingly in the following. A more detailed statistical description of the mobility-related household types formed and their frequency distribution will follow in the results section 4.2. The further characterisation in this section rather concerns the type formation process itself as well as the associated objectives.

The six types are empirically formed – based on the grouping of households according to the qualitative characteristics or rather the characteristics’ expressions they have in common. Thus, the types include and represent in accordance with their development real-world households. The typology is an analytical tool of information reduction with the objective of pattern recognition, i.e. to gain insights on differences in mobility-related emissions in connection to the mobility patterns of the household types. After all, the point is that a family household with children, for example, has different challenges and action strategies compared to a couple or single household in order to change their mobility behaviour in a way that reduces emissions. The preconditions for a change of mobility behaviour are also very different for households with and without cars. In short, if one wants to analyse mobility behaviour on the household level, it is important to know which type of household organisation is present, including the means of transport available (cf. Scheiner, 2016, pp. 691 ff.; Nobis and Kuhnimhof, 2018; Gerike *et al.*, 2020).

¹⁸ Criterion for family households: at least one child under the age of 18 years lives in the household.

Type formation as the central analytical lens and preparatory method for the detailed data evaluation had three clear objectives: (1) firstly, facilitate the data evaluation through an appropriate analytical access. (2) Secondly, improving the qualitative dimension of pattern recognition through the grouping of households along emissions- and mobility-relevant household characteristics and their respective expressions. (3) And thirdly, achieving a certain quality assurance of the results by aggregating the broad data base in relevant variables (e.g. baseline and KLIB emissions, emissions reductions, etc.) within a type. Through the application of the arithmetic mean on these variables a certain levelling of questionable data from individual cases can be achieved (cf. following section 3.3.1).

3.3 Data analysis

According to the type formation, separate data sheets were prepared for each type according to the condensed pattern defined in section 3.2.1 (data aggregation). Thus, each data sheet only comprised the households assigned to the respective type along all relevant variables, ready for the type-specific data analysis.

As in the previous methodological steps, the spreadsheet and data analysis programme Microsoft Excel (cf. section 3.2) was used for the type organisation and the statistical calculations. Furthermore, using the graphical user interface RStudio (Version: 1.2.5033, © 2009–2019 RStudio, Inc.) based on the statistical programming language R, a stand-alone analysis code was written to graphically display the statistical dispersion and location parameters of the main variables for ground mobility and air travel per type in the form of boxplots (cf. *8 Appendix B* for the corresponding boxplots).

3.3.1 Statistical methods and calculations

The main tools used in descriptive statistics were the calculation of absolute and relative frequencies, the arithmetic mean, the standard deviation of particular variables as well as a graphical analysis of dispersion and location parameters using boxplots. Furthermore, sums, differences and relative shares of variables were calculated in

order to form, in combination with the statistical tools, key figures and indicators for the analysis and comparison of the types. The following analysis steps and calculations were performed in the same way for each type.

Arithmetic mean of the variables

The calculation of the arithmetic mean is the key method to establish comparability among the variables of the different households and household types. Furthermore, it serves a certain quality assurance of the data basis, since individually questionable values from individual households are levelled with the values of other households. In this way, the data basis becomes overall more valid using the average value. However, the arithmetic mean is also sensitive to outliers. Therefore, it is reasonable to identify possible outliers of important variables through additional graphical evaluations such as boxplots.

First, the sum of the single values of all households of a type was calculated for each main variable and the variables of the individual transport modes (e.g. carsharing emissions, carsharing baseline and KLIB transport performance). By dividing the sum of each variable by the sub-sample size (n = number of people per type), the arithmetic mean as a comparable 'per capita unit' was obtained per variable for the respective type. For instance, the emissions balances of all households of a type for the baseline and KLIB real-lab year were summed and respectively the arithmetic mean calculated. This provided a comparable unit of measure per person for the respective emissions variable, the average annual emissions per capita of the type [kg CO₂-eq/person/year]. The same procedure was applied to all variables of driving or transport performances [p-km/person/year]. With the units calculated, the types could be analysed and compared consistently.

Absolute/relative differences and shares

For the main variables of ground mobility and air travel (e.g. ground mobility: baseline and KLIB total emissions, baseline and KLIB total

performance; cf. section 3.2.1 for designation) an additional ‘reduction or difference variable’ was calculated out of the respective baseline and KLIB values. This allowed the emissions reduction or difference to be determined for the RwL year 2018 (KLIB) in relation to the baseline year 2017 for each household individually and per capita and type. For instance, in terms of emissions from ground mobility and air travel, the sum of positive and negative emissions differences (of the individual households’ values) was used to calculate the average emissions reduction or increase per capita for each domain separately via the arithmetic mean. By dividing the respective ‘reduction/difference variable’ through the corresponding per capita baseline emissions, the relative positive or negative difference to the baseline emissions was obtained, i.e. specifically: by how many percent the emissions decreased or increased per capita and type in 2018 compared to 2017 in ground mobility and air travel respectively. Finally, by summing up the absolute emissions differences (positive/negative) of ground mobility and air travel, it was possible to balance and determine per type whether total emissions were effectively reduced in the mobility domain.

Similar calculations were performed for the total transport performance as well as the individual driving and transport performances of the individual modes of transport. In this way, an absolute difference value as well as a relative value with reference to the baseline was always available for each ‘performance difference variable’. This allowed performance differences in the use of transport modes to be determined relative to the baseline. For example, absolute transport performance or performance difference of the private car to be compared with that of public transport within a type or with other types. In addition, the relative share of the total transport performance was calculated for the individual modes of transport. This is practically the proportional basis for the determination of the type-specific modal split that, however, was determined by using the absolute transport performance values of the modes.

Examining type dispersion differences by standard deviation and boxplots

The emissions variables (baseline and KLIB emissions, emissions reductions/differences for ground mobility and air travel) are of central interest to this study. In addition to the calculation of the average emissions (arithmetic mean) of a type, the range and dispersion of individual emissions values (of the households) within a type and in comparison to other types is also of interest as the dispersion of per capita emissions varies according to the diversity of mobility behaviour. In order to determine the dispersion of the individual household values of the main emissions variables per type the standard deviation (SD) was calculated and a graphical evaluation using boxplots conducted.

The standard deviation indicates the extent to which collected values deviate from their average value (arithmetic mean). The lower the standard deviation, the lower the dispersion. This in turn means that the individual values of the households of one type are relatively close to each other in a narrow range and thus, depending on the variable, the per capita emissions are relatively similarly high or low or have been reduced by a similar amount. The same applies in reverse: the larger the standard deviation, the higher the dispersion, the broader the range and thus the diversity of emissions values within a type. The standard deviation of the emissions variables was calculated using the Excel '=STABW.S()' function over the individual values of the households per type.

In order to achieve an even more detailed overview of the dispersion and location parameters of the variables and to identify possible outliers, a stand-alone analysis code was written with RStudio for the generation of corresponding boxplots. The figures of the boxplots for the main emissions variables (baseline and KLIB emissions, emissions differences/reductions; from ground mobility and air travel) and for those of total transport performance by household type are provided in appendix B (cf. 8 *Appendix B*).

3.3.2 Units of measurement – key figures and indicators

CO₂-equivalent (CO₂-eq) emissions

The *CO₂-eq emissions* is a measure of the Global Warming Potential (GWP) of a greenhouse gas (GHG) and represents the emitted amount of the reference substance CO₂, that would cause the same radiative forcing, over a given period of time (usually 100 years), as an emitted amount of a particular GHG or a mixture of GHGs (IPCC, 2014). The radiative forcing factor describes the specific warming potential of a GHG in watts per square metre (W/m²) (IPCC, 2014, pp. 121, 126). The measure CO₂-eq emissions thus indicates how much an emitted amount of a GHG or a mixture of GHGs contributes to global warming compared to the same amount of CO₂. For the consideration of person-related emissions balances of the carbon tracker, covering consumption and activity-related GHG emissions across the sectors or domains, a uniform reference unit of emissions is essential for a comparable calculation basis (Schächtele and Hertle, 2007). Following this principle, all GHG emissions considered in this study are expressed in the uniform reference unit *CO₂-eq emissions* and refer with respect to the results always to the 'average emitted amount in kilogramme per person and year' [kg CO₂-eq/person/year].

Two central measures or indicators of transport statistics are particularly relevant to this study, the *transport performance* and based on this, the *modal split*.

Transport performance

Transport performance in passenger transport refers to the product of the number of persons transported (p) and the distance travelled (kilometres: km) per unit of time (t). It is accordingly measured in *passenger-kilometres* (p-km) in a certain period of time (e.g. per day or year). As a unit for describing key transport indicators, it is used to present the share of p-km travelled by a particular mode of transport or the total of all p-km travelled with all modes of transport combined (UBA, 2012, p. 66; Nobis and Kuhnimhof, 2018, p. 132). In this study's analysis, the p-km indicated to a certain

mode of transport always refers to the 'average distance travelled per person within one year' [p-km/person/year].

Modal split

The *modal split* presents the distribution of the transport performance of the main modes of transport by p-km (or ways) in percentage shares or in absolute figures. The modal split reveals the choice of transport mode (modal choice) in a city, region, country or by a specific group of transport users (UBA, 2012, p. 65; Nobis and Kuhnimhof, 2018, p. 131). In this study's analysis, the modal split (based on p-km) always refers to the 'relative transport mode use or choice of one of the types examined' (i.e. a specific group of transport users).

4 Results

The results chapter starts with a general characterisation of the sample (4.1), followed by the description of the frequency distribution of the formed mobility-related household types (4.2). Subsequently, the results concerning ground mobility are first presented with regard to emissions, reduction performance, modal choice and transport demand (4.3). This is followed by the subchapter on air travel and the associated emissions (4.4). Finally, the comparison of emissions from ground and air travel will lead to a balancing of total emissions concerning effective emissions reductions and will be broken down according to the contributions of individual modes of transport (4.5).

The following results of the data analysis focus on the remaining 63 households after the data cleansing and correction (cf. section 3.2.2).

4.1 Characterisation of the sample

The 63 households represent for 151 people living in the households. 103 (68.2 %) of these people are adults, 11 (7.3 %) are children older than 14 years and 37 (24.5 %) are children younger than 14 years. In line with the original KLIB sample (cf. Reusswig, Lass and Bock, 2020), the household size distribution deviates in this sub-sample as well from the average distribution in Berlin with slightly different values: there are less one-person households within the sample (31.7 % in the sample vs. 52.9 % in the city; StBA, 2020¹⁹), less two-person households (22.2 % in the sample vs. 27.8 % in the city; StBA, 2020) and more 3+ person households (46 % in the sample vs. 19.3 % in the city; StBA, 2020), which are exclusively family households with children. Regarding the income, the sub-sample does not differ from the overall KLIB sample analysed in the first KLIB publication (cf. Reusswig, Lass and Bock, 2020). The major share of households (39.7 %) belongs to the upper middle-income class (*equivalised disposable*

¹⁹ Own calculations based on the official household data provided by the Federal Statistical Office (StBA, 2020).

*income*²⁰: 2000 – 3000 Euro). Lower- (11.1 %), lower middle- (17.4 %) and higher-income (14.3 %) classes in relation to the Berlin net income distribution are underrepresented (cf. AfS, 2020; Eurostat, 2021). Another minor share of households (17.4 %) did not provide any information on their income. In terms of vehicle equipment, in particular the MPT, 44.4 % of the households had a private car during the tracking period of the KLIB experiment in 2018. Accordingly, 55.6 % had no private car (cf. *Table 2*, section 4.2). The latter value is slightly higher than in Berlin as a whole, where 51 % of all households do not have a car, which in turn is the highest proportion of households without a car of all regions in Germany (Nobis and Kuhnimhof, 2018). Two households (ID 113 and 116) reported owning a permanent second car, three households recorded a temporary additional holiday car. Other recorded vehicles of MPT in the sample were two motorbikes, which, however, were not used during the tracking period. The availability of bicycles per household was not documented in the initial baseline survey and could therefore only be ascertained through the tracked actual use which was the case for 89.1 % of the households.

4.2 Frequency distribution of the mobility-related household types

The six formed types differ in their share of households consequently with the same tendency as the household size distribution in the sample, since household size was used as one main distinguishing characteristic in type formation. *Table 2* presents the absolute and relative frequencies of households and persons per type in absolute figures and percentage.

²⁰ Eurostat glossary: “the equivalised disposable income is the total income of a household, after tax and other deductions, that is available for spending or saving, divided by the number of household members converted into equalised adults; household members are equalised or made equivalent by weighting each according to their age, using the so-called modified OECD equivalence scale.”(Eurostat, 2021).

Table 2: Absolute and relative frequencies²¹ of households (n=63) and persons (n=151) per type.

Households per type	Single (n=20; 31.7 %)		Couple (n=14; 22.2 %)		Family (n=29; 46 %)	
	Absolute [n]	Relative [%]	Absolute [n]	Relative [%]	Absolute [n]	Relative [%]
With car (n=28; 44.4 %)	8	12.7	7	11.1	13	20.6
No car (n=35; 55.6 %)	12	19.0	7	11.1	16	25.4
Persons per type	Single (n=20; 13.2 %)		Couple (n=28; 18.5 %)		Family (n=103; 68.2 %)	
	Absolute [n]	Relative [%]	Absolute [n]	Relative [%]	Absolute [n]	Relative [%]
With car	8	5.3	14	9.3	47	31.1
No car	12	7.9	14	9.3	56	37.1

The family types clearly dominate the sample in numbers of households per type and correspondingly also in persons per type. Together they account for 46 % of the households (FWC 20.6 %, FNC 25.4 %) and 68.2 % of all persons (FWC 31.1 %, FNC 37.1 %) within the sample of which again 46.6 % are children (48 of 103 persons). The children shares within the family types are approximately equal (FWC 46.8 %, FNC 46.4 %). The single types together represent 31.7 % of all households (SWC 12.7 %, SNC 19 %) but just 13.2 % of all persons (SWC 5.3 %, SNC 7.9 %) in the sample. With a combined share of 22.2 %, the couple types again comprise less of the households (CWC 11.1 %, CNC 11.1 %) than the single types, but with 18.5 % more of the persons (CWC 9.3 %, CNC 9.3 %).

4.3 Ground mobility

As a starting point this subchapter will firstly focus on the comparative description of the household types' emissions balances and emissions reductions within ground mobility (4.3.1). The second part (4.3.2) evaluates the modal choice, transport demand per mode and the respective differences of the KLIB year 2018 compared to the baseline year 2017 per household type. The description of the individual types is followed by a comparison of the types within each of the main groups (car-owning and car-free household types). For a coherent evaluation of the mobility patterns and

²¹ Deviations of 100 % due to rounding differences.

associated emissions, the analysis distinguished between the main means and prevalent groups of modes of passenger transport. In line with the major mobility studies in Germany MID and SrV, an analytical distinction was made between the MPT, effectively represented by the private car, carsharing, bike, on foot²² and public transport (cf. section 3.2.1; Nobis and Kuhnimhof, 2018; Gerike *et al.*, 2020).

4.3.1 Emissions balances and reduction performance

Figure 5 shows the baseline and KLIB per capita emissions in ground mobility per household type and compared to the German average. First of all, it is noticeable that all types, except the SWC type, show a lower baseline and KLIB emissions balances than the German average which lays at approximately 1600 kg CO₂-eq per capita and year for ground mobility alone. Furthermore, five out of six household types present decreased emissions balances for the KLIB year 2018 compared to the baseline 2017.

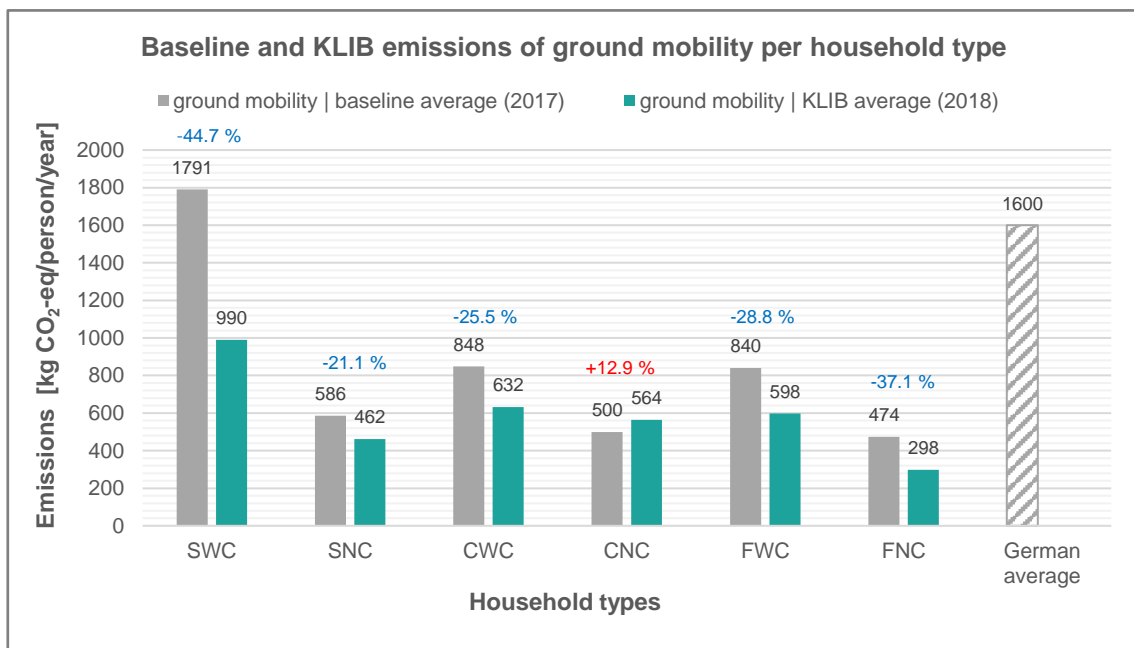


Figure 5: Baseline (2017) and KLIB (2018) average emissions [kg CO₂-eq/person/year] of ground mobility per household type in comparison with German average (1.600 kg CO₂-eq/person/year). Total values are presented directly above bars. Relative differences of KLIB performance in relation to the baseline are shown above bar couple per type in percentage: reductions (blue) or increases (red).

²² In practical planning terminology and evaluations of household-related mobility, ‘on foot’ is also referred to as a means of transport (Gerike *et al.*, 2020).

In the following the details on the emissions and performance differences are described, starting with the baseline situation of the types.

The per capita emissions in ground mobility for the baseline year show partly different initial situations of the household types. The highest baseline per capita emissions exhibits the SWC type with 1.791 kg CO₂-eq (SD=1371), the lower end marks the FNC type presenting baseline emissions in the amount of 474 kg CO₂-eq (SD=325). The second lowest baseline emissions shows the CNC type with 500 kg CO₂-eq (SD=259), followed by SNC with somewhat higher emissions of 586 kg CO₂-eq (SD=571). The types FWC with 840 kg CO₂-eq (SD=406) and CWC with 848 kg CO₂-eq (SD=282) exhibit an almost equal initial situation. It is worth noting that all car-owning household types show clearly higher baseline emissions balances than their pendant types without cars (cf. *Figure 5*).

For the yearlong KLIB project phase all household types present emissions reductions in ground mobility except for the CNC type, which shows a slight increase. Having a closer look at the individual types, the largest emissions reductions were achieved by the SWC type. Households of this type managed to reduce their emissions on average by 801 kg CO₂-eq (SD=1335) per capita to 990 kg CO₂-eq (SD=407) per capita in 2018 which is 44.7 % less than in 2017 (cf. *Figure 5*). Despite the highest emissions reductions of all types, the SWC type nonetheless shows the highest KLIB emissions balance in ground mobility for 2018, same as for the baseline. Relatively high absolute reductions within ground mobility were also achieved by the two other types with private cars and approximately equal baseline emissions. The FWC type reduced emissions by 242 kg CO₂-eq (SD=548) compared to the baseline and reached therewith a 28.8 % lesser KLIB emissions balance of 598 kg CO₂-eq (SD=392) per capita. For the CWC type, ground mobility emissions decreased by 216 kg CO₂-eq (SD=244) in 2018 to a KLIB emissions balance of 632 kg CO₂-eq (SD=288), 25.5 % less than the baseline balance (cf. *Figure 5*). The absolute reductions of the FNC type with 176 kg CO₂-eq (SD=283) are somewhat lower, but compared to its own baseline balance these are 37.1 % less emissions. This relative value is striking as households of this type on average already

exhibit the lowest baseline emissions of all types. In relation to their already low baseline emissions, they nevertheless managed to reduce emissions comparatively strongly. Hence, their KLIB emissions balance of 298 kg CO₂-eq (SD=468) per capita is also the lowest of all types within ground mobility at the end of the tracking period. With emissions reductions of 124 kg CO₂-eq (SD=676), the SNC type reduced less than the four types just described in absolute figures, but still presents with 463 kg CO₂-eq (SD=300) per capita the second lowest KLIB emissions balance. The CNC type in turn increased its emissions by 64 kg CO₂-eq (SD=394) as already mentioned. Thus, the KLIB balance with 564 kg CO₂-eq (SD=308) per capita is 12.9 % higher than the baseline emissions balance.

The description and comparison of baseline and KLIB emissions balances in ground mobility reveal that the highest absolute emissions reductions were consistently achieved by the car-owning household types (SWC, CWC, FWC). However, they also consistently show the highest baseline and KLIB emissions balances. The household types without private cars have correspondingly lower baseline and KLIB emissions balances than their counterparts. The SNC and FNC types reduced less emissions in absolute figures. However, in comparison to its own baseline emissions balance, the FNC type still decreased emissions noticeably. One exception is the CNC type that as the only one increased its emissions. For an overview on descriptive statistics dispersion and location parameters of the baseline and KLIB emissions variables (cf. *Figure 24*) as well as the difference/reduction variables (cf. *Figure 23*) of ground mobility per household type see appendix B (cf. *8 Appendix B*), which presents the corresponding boxplots.

4.3.2 Modal choice and transport demand

This section presents the results in relation to the modal choice and transport demand of the individual household types. In this respect the *modal split* and *transport performance* of the respective modes will be analysed with the focus on the KLIB real-lab year compared to the baseline year. First, the mobility patterns of the car-owning household types are described individually and then compared with each other. Subsequently, the same procedure will follow for the car-free household types to allow a

more consistent comparison of transport use. The individual type descriptions will concentrate on the modal split and the differences in transport performance with a focus on the KLIB year, but with reference to the baseline 2017. The type comparisons within the main groups (car-owning and car-free household types) will furthermore identify differences in total values of 2018 per mode of transport as well as differences in modal shift among the types.

Single with car type (SWC)

Starting with the SWC type, *Figure 6* illustrates the modal split of the baseline (2017) versus the modal split of the KLIB year (2018). It shows a clear decrease of the private car share (-9.8 %) on the modal split within the KLIB project phase compared to the baseline year. In contrast, the modal shares of the environmental alliance of bike (+1.2 %) and public transport systems (+6.4 %) increased. Carsharing use also increased slightly (+2.1 %) within 2018. Nevertheless, the private car remains the main mode of transport in 2018 of the SWC type encompassing 49.1 % (7822 p-km) of average passenger-kilometres travelled in 2018. In second place is public transport with 38.6 % (6148 p-km), then by a long shot bike with 8.2 % (1307 p-km) and finally carsharing with exactly 4 % (644 p-km) modal share. The average transport performance per modus in passenger-kilometres per person and year is presented in *Figure 7*. It shows an increase of average total transport performance by 1374 p-km (+9.4 %) within 2018 to a total of 15921 p-km per capita. A closer look at the individual mode of transport reveals a decrease in transport performance of the private car by 742 p-km (-8.7 %) per capita. All other modes of transport show distinct increases during 2018: led by public transport with 1459 p-km (+31.1%), car sharing with 363 p-km (+129%) and

bike with 295 p-km (+29.1%) per capita and year (cf. Figure 7). There were no p-km recorded for the mode on foot within the SWC type.

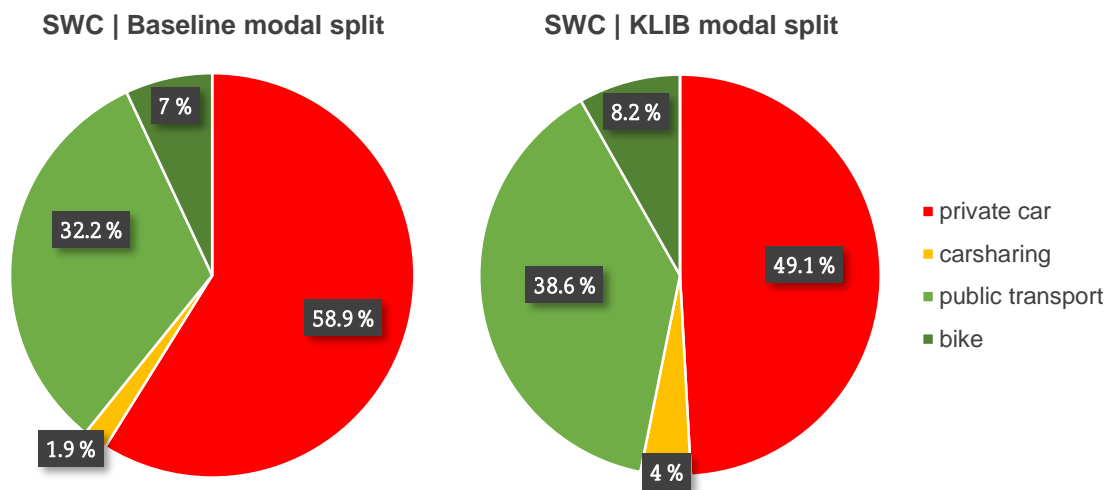


Figure 6: Baseline (2017) and KLIB (2018) modal split of the SWC type. Percentage share of private car, carsharing, public transport and bike based on transport performance [p-km]. On foot is neglected as no p-km were recorded within SWC type. Deviations of 100

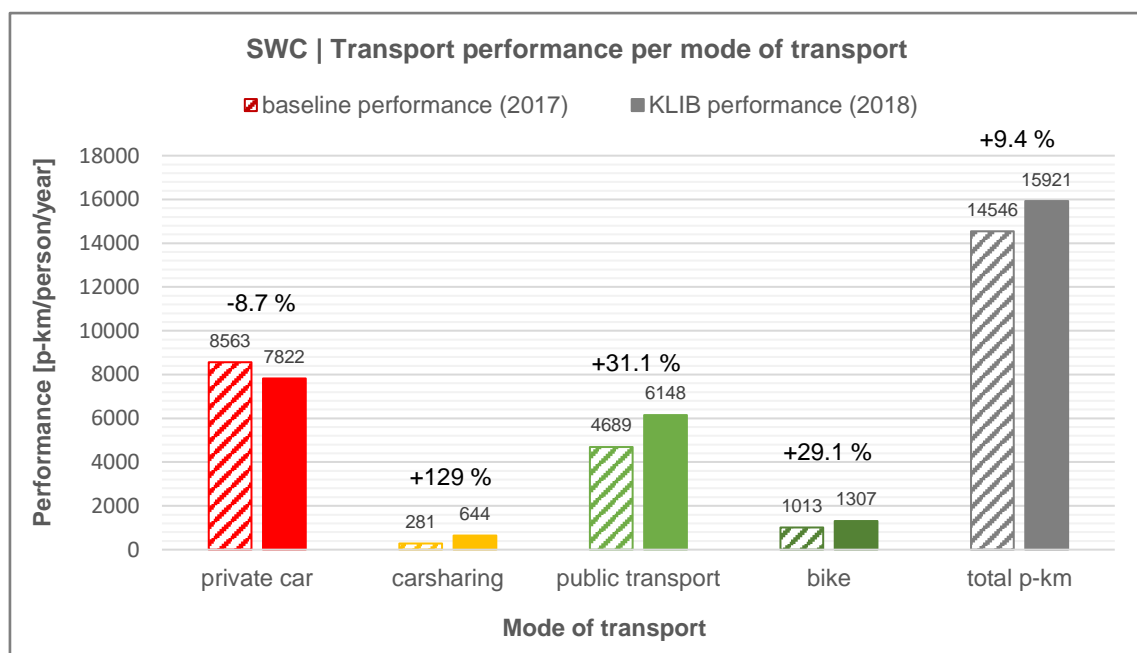


Figure 7: Transport performance per mode of transport (2017: dashed | 2018: filled) of the SWC type. Transport performances [p-km/person/year] of private car, carsharing, public transport, bike and total transport performance (total p-km). Total values are presented directly above bars. Relative differences of KLIB performance in relation to baseline are shown above bar couple per mode of transport in percentage.

Couple with car type (CWC)

Comparing the baseline and KLIB modal split of the CWC type, presented in *Figure 8*, shows likewise a decrease in the share of the private car (-6.7 %) along a clear increase of public transport (+12.6 %) in 2018. Striking in connection with the project's objective is the distinct decline of the bike modal share (-6.2 %). The carsharing share increased marginally (+0.3 %). Through the strong increase in modal share, the public transport replaces the private car as the main mode of transport accounting for 51.1 % (3783 p-km) of average p-km travelled within 2018. However, the private car is still a major mode of transport with a modal share of 39 % (2892 p-km). The bike accounts for a much lower share with 9.3% (686 p-km), followed by carsharing with 0.6% (46 p-km).

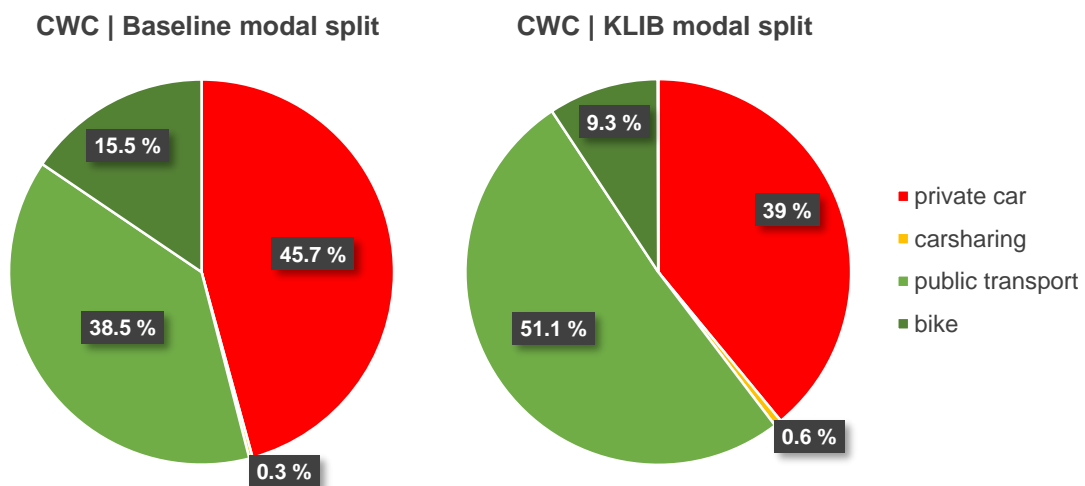


Figure 8: Baseline (2017) and KLIB (2018) modal split of the CWC type. Percentage share of private car, carsharing, public transport and bike based on transport performance [p-km]. On foot is neglected due to minor share (baseline: 0 %; KLIB: 0.03 %). Deviations of 100 % due to rounding differences.

Considering the respective average transport performances in absolute figures, shown in *Figure 9*, reveals a distinct reduction of 622 p-km (-17.7 %) in private car use and an opposite increase of 826 p-km (+27.9 %) per capita in public transport performance. Already indicated by the reduced modal share in 2018, a strong reduction in bike performance of 507 p-km (-42.5 %) is observable. Carsharing performance more than doubled but remains at a relatively low level with 46 p-km (+112.3 %)

travelled per capita. For on foot, no p-km were recorded for the baseline and around 3 p-km per capita for the KLIB year. Average total transport performance decreased slightly by 276 p-km (-3.6 %) and finally totalled 7410 p-km per capita (cf. *Figure 9*).

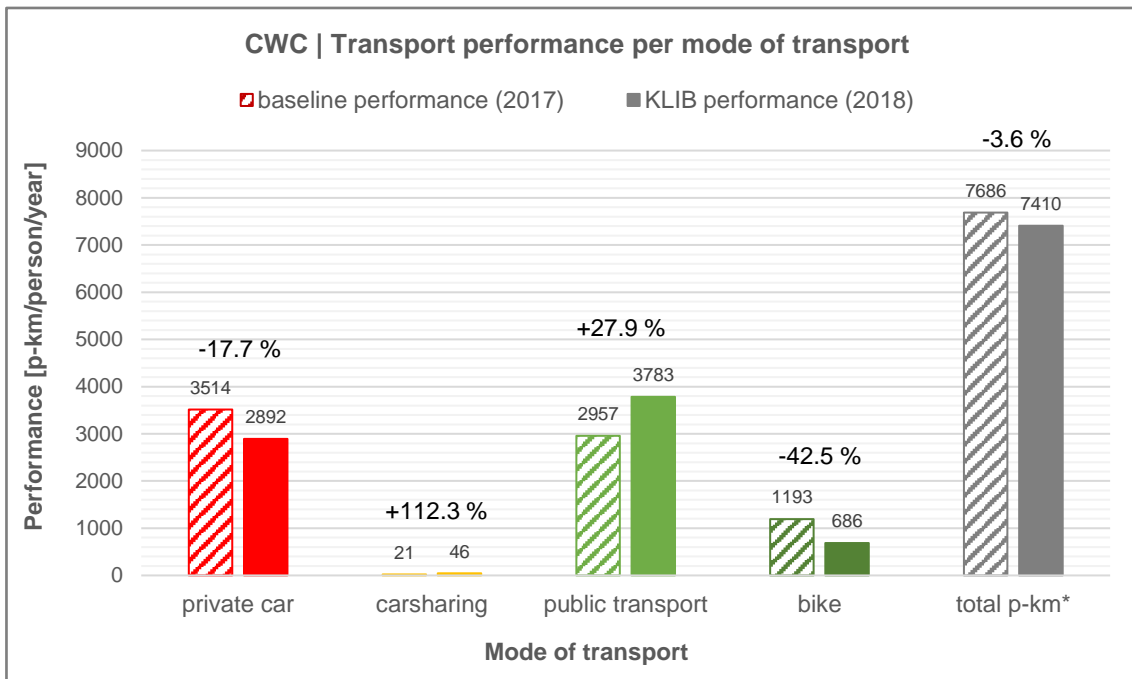


Figure 9: Transport performance per mode of transport (2017: dashed | 2018: filled) of the CWC type. Transport performances [p-km/person/year] of private car, carsharing, public transport, bike and total transport performance (total p-km). Total values are presented directly above bars. Relative differences of KLIB performance in relation to baseline are shown above bar couple per mode of transport in percentage. *total p-km include 3 p-km on foot performance not shown here.

Family with car type (FWC)

Figure 10 comparatively illustrates the baseline and KLIB modal split of the FWC type. It shows again a decline of the private car share (-4.9 %) and an increase of the public transport modal share (+6.2 %) in 2018 compared to the baseline 2017. Also within the FWC type, a clear decline of the bike modal share (-6 %) is to be stated. Carsharing modal share (+4.1 %) on the other hand increased. The increased share of public transport led to an approximately equal use of private car with 42.7 % (2090 p-km) and public transport with 42.5 % (2080 p-km) in 2018, representing the two main modes of transport for the FWC type. In third place is the bike with 10.1 % (494 p-km),

followed by carsharing with 4.1 % (201 p-km) and on foot with 0.6 % (28 p-km) of total p-km per capita travelled in 2018.

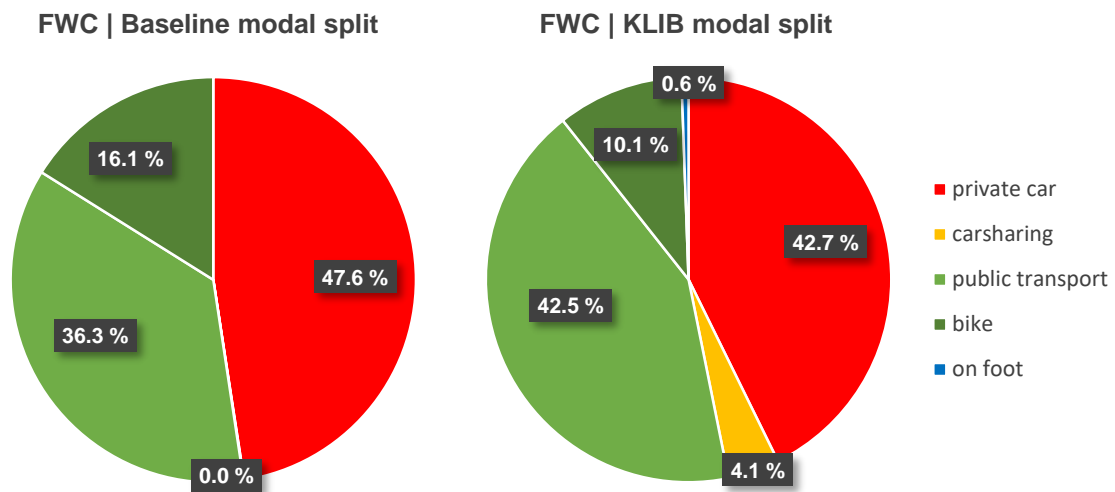


Figure 10: Baseline (2017) and KLIB (2018) modal split of the FWC type. Percentage share of private car, carsharing, public transport, bike and on foot based on transport performance [p-km]. Deviations of 100 % due to rounding differences.

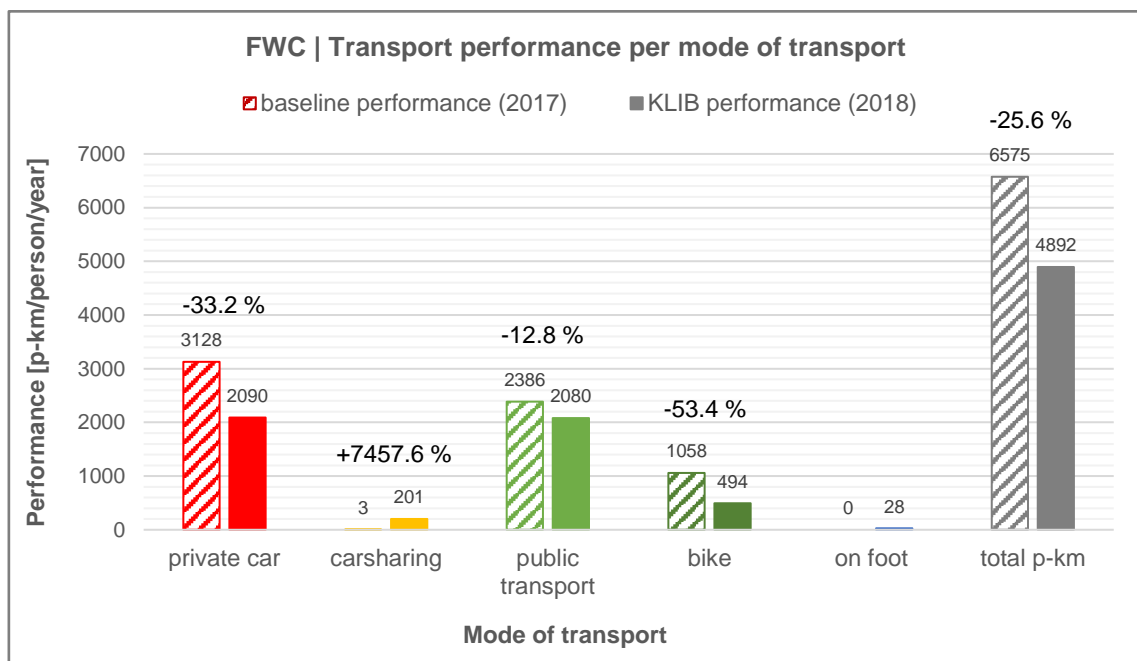


Figure 11: Transport performance per mode of transport (2017: dashed | 2018: filled) of the FWC type. Transport performances [p-km/person/year] of private car, carsharing, public transport, bike, on foot and total transport performance (total p-km). Total values are presented directly above bars. Relative differences of KLIB performance in relation to baseline are shown above bar couple per mode of transport in percentage.

The average transport performances per modus, presented in *Figure 11*, show a more differentiated picture. In fact, the private car performance strongly decreased by 1038 p-km (-33.2 %). Despite the modal share relative increase of public transport, its transport performance also declined by 306 p-km (-12.8 %). Bike performance clearly decreased by 494 p-km (-53.4 %). Only carsharing with 198 p-km (+7457.6 %) shows an increase in transport performances. No baseline values were recorded for on foot, but 28 p-km per capita for the KLIB year. The distinct declines in transport performances of private car, bike and public transport are consequently reflected in a sharp drop of total transport performance by 1683 p-km (-25.6 %) to a total of 4892 p-km per capita in 2018 (cf. *Figure 11*).

Comparison of car-owning types (SWC, CWC, FWC)

Comparing the three car-owning household types, the SWC type shows the highest per capita total transport performance in both the baseline and KLIB year (cf. *Figure 7, Figure 9, Figure 11*). With 15921 p-km per capita within 2018, its 2.15 times higher than the CWC type's with 7410 p-km and 3.25 times higher than the FWC type's total transport performance with 4892 p-km. The high total transport performance is largely due to the overall strong use of the private car within the SWC type as the main mode of transport but also due to public transport. Correspondingly, the SWC type also marks the highest transport performance of the private car in absolute figures (SWC: 7822 p-km; CWC: 2892 p-km; FWC: 2090 p-km; cf. *Figure 7, Figure 9, Figure 11*) as well as the according highest modal share among the three types (SWC: 49.1 %; CWC: 39 %; FWC: 42.7 %; cf. *Figure 6, Figure 8, Figure 10*). However, the strongest decline in private car transport performance was achieved by the FWC type (FWC: -1038 p-km; SWC: -742 p-km; CWC: -622 p-km). Nevertheless, in terms of modal share the private car is approximately of equal relevance with public transport within the FWC type (private car: 42.7 %, public transport: 42.5 %, cf. *Figure 10*) whereas public transport became the main mode of transport within the CWC type in 2018 (public transport: 51.1 %, cf. *Figure 8*). The comparatively highest increase and total value of public transport performance in 2018, again shows the SWC type (+1459 p-km, total:

6148 p-km, cf. *Figure 7*), followed by the CWC type (+826 p-km, total: 3783 p-km, cf. *Figure 9*). By contrast, the FWC type (-306 p-km, total: 2090 p-km, cf. *Figure 11*) revealed a declining public transport performance in 2018.

With regard to the bike transport performance the three types were in total relatively close together in 2017 (CWC: 1193 p-km; FWC: 1058 p-km; SWC: 1013 p-km; cf. *Figure 7, Figure 9, Figure 11*) with the CWC type having a slightly higher value. Strikingly, as above mentioned, performance declined for the CWC and FWC types approximately similar (CWC: -507 p-km; FWC: -565 p-km) and only increased for the SWC type (SWC: +295 p-km). The SWC type therefore presents the highest bike transport performance of the three types in 2018 (SWC: 1307 p-km; CWC: 686 p-km; FWC: 494 p-km; cf. *Figure 7, Figure 9, Figure 11*). Nonetheless, due to the overall lower total transport performance of the CWC and FWC types, both in turn reveal a proportionally higher bike modal share in 2018 compared to the SWC type (FWC: 10.1 %; CWC: 9.3 %; SWC: 8 %; cf. *Figure 6, Figure 8, Figure 10*). Carsharing's transport performance increased throughout the three types with the strongest increase observable within the SWC type, followed by the FWC and the least within the CWC type (SWC: +363 p-km; FWC: +198 p-km; CWC: +24 p-km). Accordingly, the SWC type states the highest total carsharing transport performance in 2018 (SWC: 644 p-km; FWC: 201 p-km; CWC: 46 p-km; cf. *Figure 7, Figure 9, Figure 11*). It should be mentioned that the baseline value of the SWC type was already higher than the other type's which presented overall low values for carsharing in 2017 (SWC: 281 p-km; CWC: 21 p-km; FWC: 3 p-km; cf. *Figure 7, Figure 9, Figure 11*). However, carsharing modal shares of all three household types are relatively low compared to other modes of transport (SWC: 4 %; FWC: 4.1 %; CWC: 0.6 %; cf. *Figure 6, Figure 8, Figure 10*). On foot performance was not tracked in the baseline survey of 2017. Within 2018 there were no p-km recorded for the SWC type and a neglectable low value for the CWC type (2.6 p-km). Only the FWC type showed some on foot performance per capita within 2018 (47 p-km; cf. *Figure 11*) but also with a minor modal share (0.6 %, cf. *Figure 10*).

Single no car type (SNC)

The KLIB modal split of the SNC type, shown in *Figure 12*, presents little deviation in the modal share of the public transport with a minor decrease (-2.2 %) compared to the baseline. The bike modal share decreased a little stronger (-6.6 %) whereas car-sharing remarks increases (+8 %) in modal share compared to the baseline. Public transport represents the main mode of transport encompassing 67 % (8693 p-km) of average p-km travelled in 2018, followed by bike with 21.6 % (2803 p-km), carsharing with 10.6 % (1380 p-km) and on foot, representing the lowest share with 0.7 % (90 p-km). The average transport performance per modus, illustrated in *Figure 13*, shows a clear increase of 958 p-km (+12.4 %) in transport performance of the public transport despite its declining modal share. The bike's transport performance in turn declines by 347 p-km (-11 %) per capita in 2018. Carsharing reveals the strongest increase in transport performance with 1091 p-km (+377.3 %). On foot shows a total of 90 p-km per capita for 2018, baseline values were not recorded. Total transport performance increased distinctly by 1792 p-km (+16 %) due to the gains of carsharing and public transport and totalled 12966 p-km per capita in 2018.

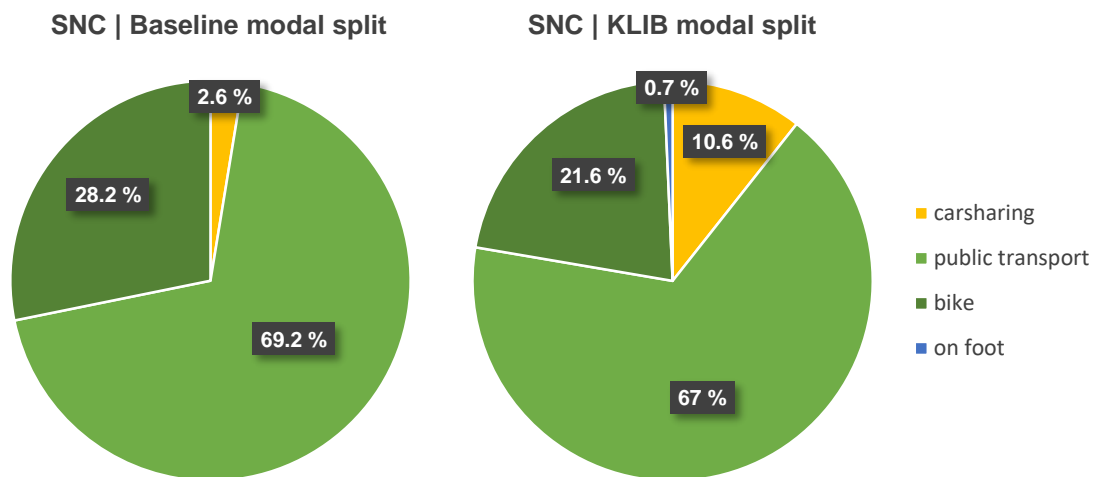


Figure 12: Baseline (2017) and KLIB (2018) modal split of the SNC type. Percentage share of carsharing, public transport, bike and on foot based on transport performance [p-km]. Deviations of 100 % due to rounding differences.

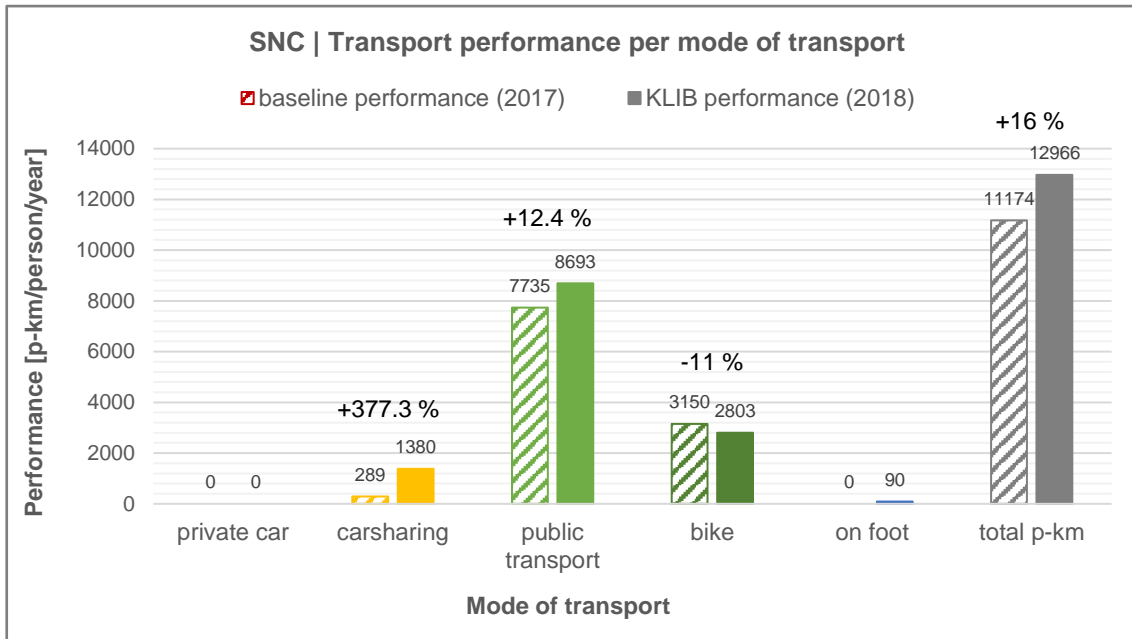


Figure 13: Transport performance per mode of transport (2017: dashed | 2018: filled) of the SNC type. Transport performances [p-km/person/year] of carsharing, public transport, bike, on foot and total transport performance (total p-km). Total values are presented directly above bars. Relative differences of KLIB performance in relation to baseline are shown above bar couple per mode of transport in percentage.

Couple no car type (CNC)

Figure 14 contrasts the baseline and KLIB modal split of the CNC type. Public transport records a clear increase (+9.8 %) in modal share within 2018 compared to the baseline. A decline (-7 %) again is observable for the bike and carsharing also shows a decreasing modal share (-3.2 %). The main mode of transport within the KLIB year 2018 is thus public transport with 80.3 % (10006 p-km) modal share, the bike is second in use with 11.7 % (1464 p-km), followed by carsharing with 7.7 % (964 p-km). On foot though shows the smallest share of 0.2 % (31 p-km). Average transport performance in absolute figures, shown in Figure 15, reveals increases in p-km for all modes of transport. Public transport performance almost doubled along a strong gain of 4.731 p-km (+89.7 %). The bike's transport performance heightened slightly by 66 p-km (+4.7 %) and carsharing's a little stronger by 150 p-km (+18.4 %) per capita in 2018. The large increase in public transport performance in particular consequently led to a distinct growth in total transport performance, which increased 2018 by 4978 p-km (+66.5%) to a total of 12465 p-km per capita.

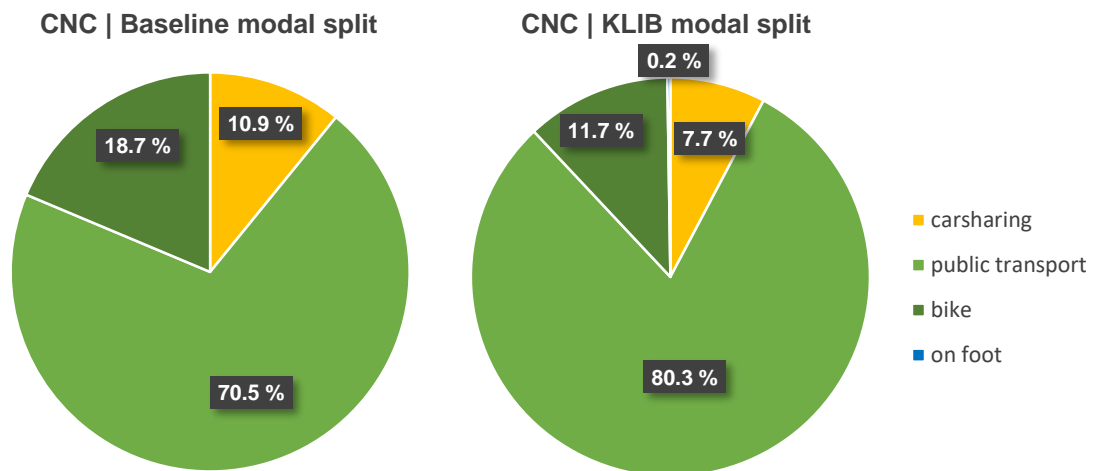


Figure 14: Baseline (2017) and KLIB (2018) modal split of the CNC type. Percentage share of carsharing, public transport, bike and on foot based on transport performance [p-km]. Deviations of 100 % due to rounding differences.

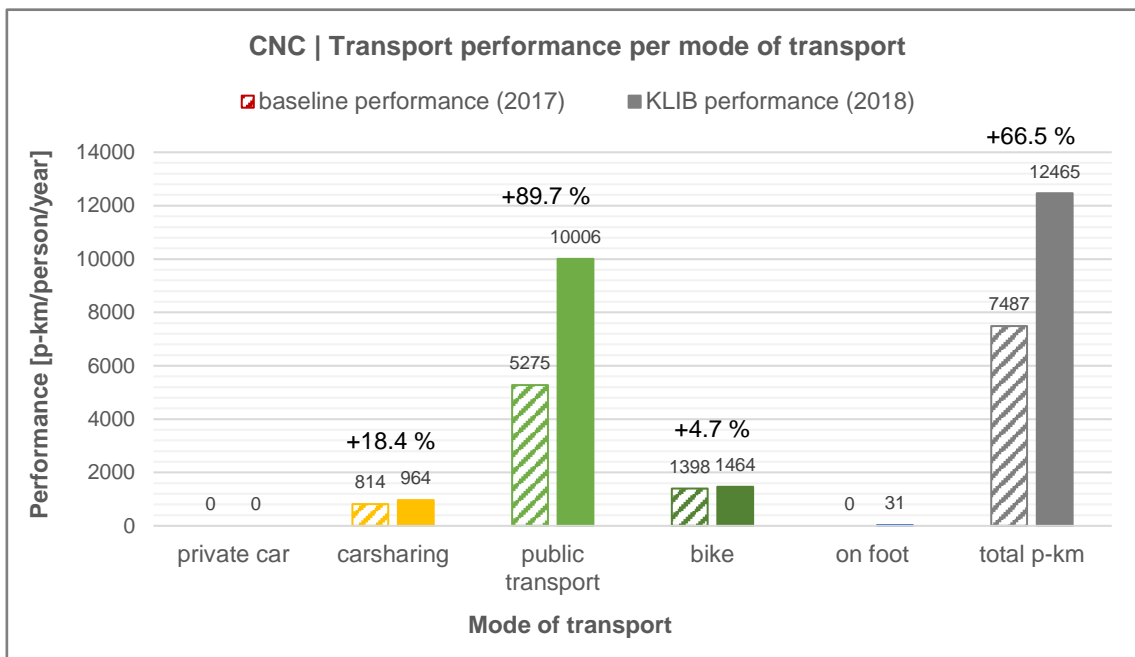


Figure 15: Transport performance per mode of transport (2017: dashed | 2018: filled) of the CNC type. Transport performances [p-km/person/year] of carsharing, public transport, bike, on foot and total transport performance (total p-km). Total values are presented directly above bars. Relative differences of KLIB performance in relation to baseline are shown above bar couple per mode of transport in percentage.

Family no car type (FNC)

Comparing the FNC type's baseline and KLIB modal split, shown in *Figure 16*, it is noticeable that the baseline modal split states some modal share for the private car while it's a missing mode²³ in the KLIB year. At the type level, this means an average reduction in private car usage of 100 % for the FNC type in 2018. By contrast, the modal share of public transport increased clearly (+12.8 %), which thus still represents the main mode in transport with 79.9 % (4837 p-km) in 2018. Carsharing modal share heightened (+0.6 %) marginally to 11 % (667 p-km). The Bike share in turn declined (-6.9 %) to 8.3 % (501 p-km). Hence, the bike was less used as a transport mode than carsharing in 2018. In relation to the distance travelled, however, the modal share of on foot is lowest at 0.8 % (51 p-km). *Figure 17* presents the average transport performance per modus, which confirms the trends observed in the comparison of the modal splits in a differentiated manner. The transport performance of the public transport increased strongly by 1375 p-km (+39.7 %) per capita. Carsharing transport performance records an increase of 133 p-km (+25 %). The bike shows a clear decline

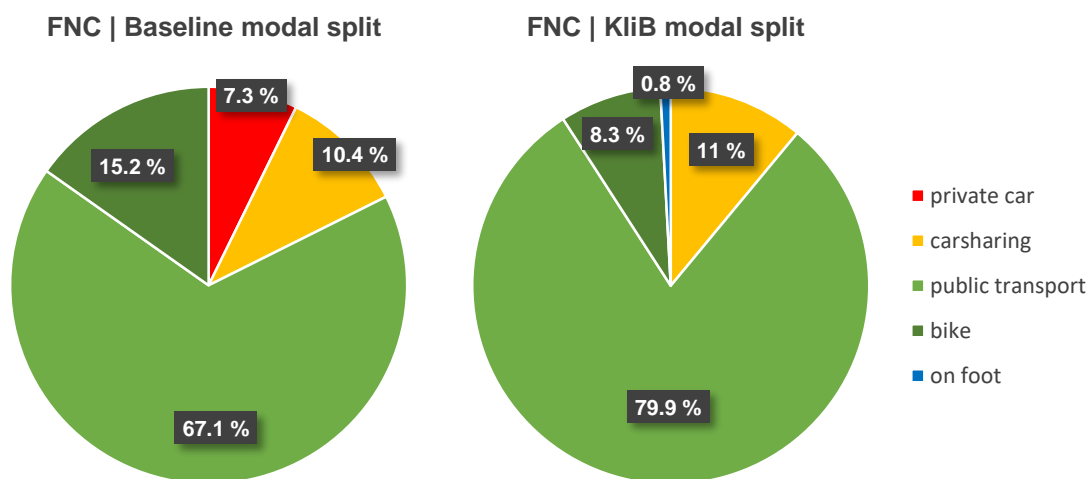


Figure 16: Baseline (2017) and KLIB (2018) modal split of the FNC type. Percentage share of private car, carsharing, public transport, bike and on foot based on transport performance [p-km]. Deviations of 100 % due to rounding differences.

²³ Two households (ID 65 and 68) within the FNC type recorded and used a private car in 2017. They must have sold or simply not used them in 2018. At least no private car was recorded nor transport performance tracked for the KLIB year.

of 285 p-km (-36.1 %) in average transport performance. Mainly due the strong increases in public transport performance, the total transport performance for the FNC type also heightened in average by 902 p-km and therewith totalled 6.057 p-km per capita in 2018.

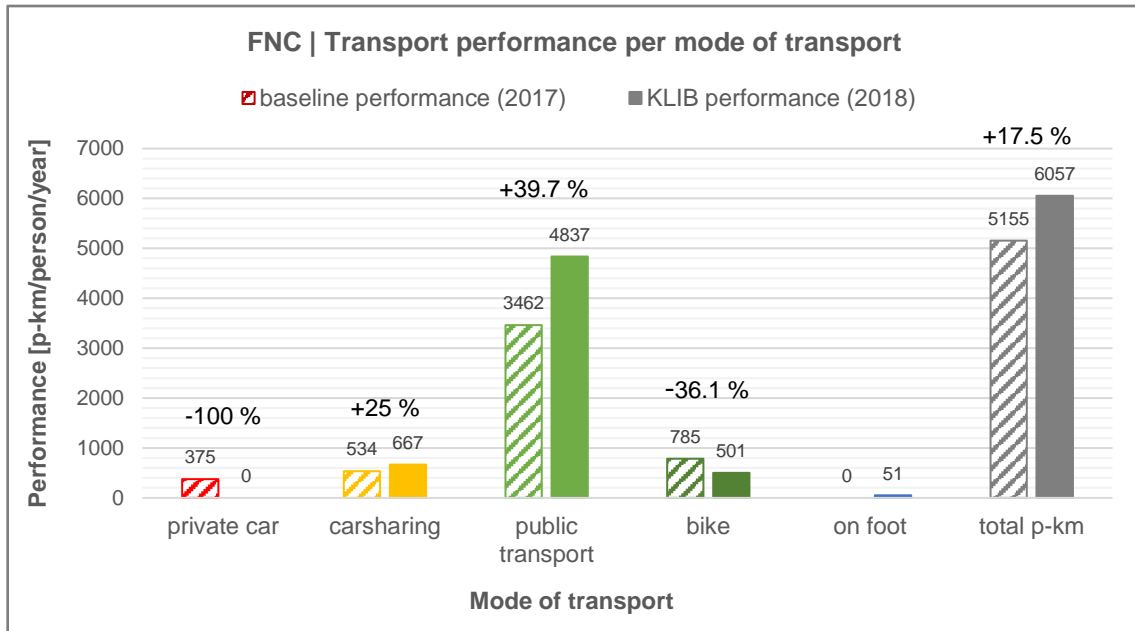


Figure 17: Transport performance per mode of transport (2017: dashed | 2018: filled) of the FNC type. Transport performances [p-km/person/year] of private car, carsharing, public transport, bike, on foot and total transport performance (total p-km). Total values are presented directly above bars. Relative differences of KLIB performance in relation to baseline are shown above bar couple per mode of transport in percentage.

Comparison of car-free types (SNC, CNC, FNC)

If one compares the three types without a car, the SNC type shows the highest total transport performance in both the baseline and KLIB year (cf. *Figure 13*, *Figure 15*, *Figure 17*). Within the KLIB year 2018 the SNC totalled 12966 p-km per capita, closely followed by the CNC type with 12465 p-km. A far lower total transport performance presents the FNC type with an average of 6057 p-km per capita. Hence, people within the former types on average travelled more than twice as many p-km in 2018 compared to people of the FNC type. The high total transport performance of both the SNC and CNC types is mainly due to the strong use of public transport which absolute figures reveal (cf. *Figure 13*, *Figure 15*). Highest increases in public transport

performance among the three types is distinctly recorded by the CNC type (CNC: +4.731 p-km; SNC: 1792 p-km; FNC: 1375 p-km). Concurring, it tracks both the highest transport performance (CNC: 10006 p-km; SNC: 8693 p-km; FNC: 4837 p-km; cf. *Figure 13, Figure 15, Figure 17*) and the highest modal share (CNC: 80.3 %; FNC: 79.9 %; SNC: 67 %; cf. *Figure 12, Figure 14, Figure 16*) of public transport within 2018. In terms of modal share, however, the FNC type catches up closely in proportion. Ultimately, public transport is the most important mode of transport within all three types in both years, although with shares still clearly rising for the CNC and FNC types in 2018 (cf. *Figure 12, Figure 14, Figure 16*).

Bike transport performance declined within the SNC and FNC type (FNC: -284 p-km; SNC: -347 p-km) and only increased marginally within the CNC type (CNC: +66 p-km). Nevertheless, the SNC type shows the highest average values in bike performance for 2018 among all types (SNC: 2803 p-km; CNC: 1464 p-km; FNC: 501 p-km; cf. *Figure 13, Figure 15, Figure 17*) and further a considerable bike modal share (SNC: 21.6 %; cf. *Figure 12*). The CNC type shows a distinctly lower bike modal share, followed by the FNC type's again somewhat lower share (CNC: 11.7 %; FNC: 8.3 %; cf. *Figure 14, Figure 16*). The upward trend in carsharing observed among car-owning types is also evident among the car-free types: all three types presenting increases in carsharing transport performance, which in turn are largest within the SNC type (SNC: 1091 p-km; CNC: 150 p-km; FNC: +133 p-km). Correspondingly, the SNC records the highest total car-sharing performance of the three types in 2018 (SNC: 1380 p-km; CNC: 964 p-km; FNC: 667 p-km; cf. *Figure 13, Figure 15, Figure 17*) while showing the lowest in 2017. The carsharing modal shares of the FNC and SNC type are close to each other in 2018 (FNC: 11 %; SNC: 10.6 %; cf. *Figure 16*) despite their clear difference in absolute figures. Only the CNC type presents a slightly lower share (CNC: 7.7 %; cf. *Figure 14*). On foot performance was not recorded in the baseline survey of 2017. However, contrary to the car-owning types, all three car-free types tracked some on foot performance. The SNC type exhibits the highest performance, the lowest is recorded by the CNC type (SNC: 90 p-km; FNC: 51 p-km ; CNC: 31 p-km; cf. *Figure 13, Figure 15, Figure 17*). In terms of on foot modal share, the FNC type presents the highest share with only little

difference to the SNC type. Accordingly, the CNC shows the lowest share (FNC: 0.8 %; SNC: 0.7 %; CNC: 0.2 %; cf. *Figure 12, Figure 14, Figure 16*).

Interim summary of modal choice and transport demand

There are partially considerable differences observable between the household types in terms of modal choice and transport demand. The differences between the car-owning and car-free types obviously relate to a large extent to the upstream decision of car acquisition. However, the individual household types within the main groups also show pronounced differences in their mobility behaviour. Hence, it is worth to sum up the observable patterns.

Within the KLIB year the private car consistently loses modal shares along a clearly reduced transport performance among the car-owning household types. In turn, with exception within the FWC type, the relevance of public transport is increasingly challenging and partially replacing the private car as the main mode of transport. If the private car drops out as a mobility option, the public transport is consistently of predominant relevance, representing the main mode of transport. Strikingly in relation to the emissions reduction goal of the KLIB project is the fact that four (CWC, FWC, SNC, FNC) out of six types show a decreasing bike transport performance in 2018. Nevertheless, it is a relevant mode of transport for all types and varies most with modal shares around 10 % (+/- 1.8 %) within KLIB, except for the SNC type with a clearly higher share. Carsharing in turn records consistently increasing transport performances with partially distinctly higher total values for the household types without a private car. Recorded on foot performance played a minor role within 2018. Highest total transport performances per capita are shown by the single household types (SWC, SNC), followed by the couple types (CNC, CWC). The lowest total transport performances are presented by the family types. (FNC, FWC). No clear trend can be identified for the influence of *car ownership* on total transport performance: while the SWC type shows a higher total transport performance than the SNC type, it is the other way round for the CNC and CWC types as well as for the FNC and FWC types. The types

without a private car show clear increases in total transport performance compared to the baseline, whereas except for the SWC type, the car-owning types show decreases in total transport performance.

4.4 Air travel

In this section the emissions balances for the KLIB and baseline year of the household types will be described comparatively and ranked in relation to the other types and the German average. The focus is again on revealing differences in emissions per type and their range in comparison to the other types.

Figure 18 maps the baseline and KLIB per capita emissions of air travel per household type and compared to the German average. Before going into detail there are two noteworthy aspects directly observable. The trend in air travel is exactly the opposite of that in ground mobility: while for the ground mobility all types revealed emissions far below the German average in 2018 (cf. *Figure 5*), for air travel they show consistently emissions well above the German average of approximately 580 kg CO₂-eq per capita and year. Furthermore, with the exception of the FNC type, all other household types show partially strongly increased emissions balances within 2018 compared to 2017. In the following, the details per type are described.

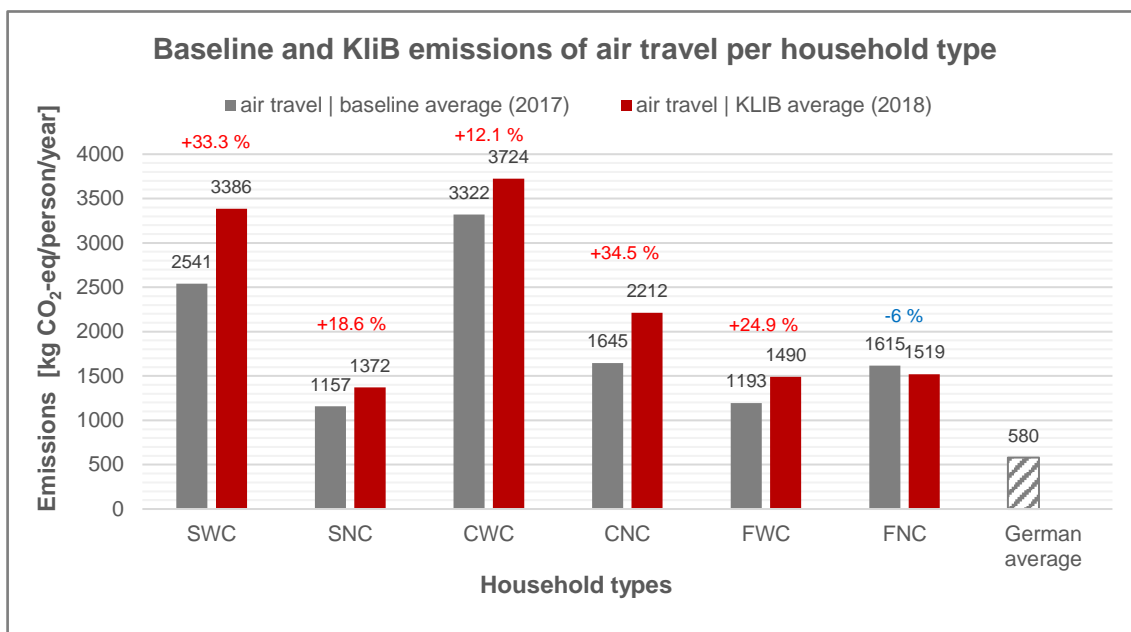


Figure 18: Baseline (2017) and KLiB (2018) average emissions [kg CO₂-eq/person/year] of air travel per household type in comparison with German average (580 kg CO₂-eq/person/year). Total values are presented directly above bars. Relative differences of KLiB performance in relation to the baseline are shown above bar couple per type in percentage: reductions (blue) or increases (red).

Two household types stand out in air travel emissions: the CWC and SWC types. Both types already show the highest per capita emissions for the baseline, the CWC type again higher with 3322 kg CO₂-eq (SD=5924) than the SWC type with 2541 kg CO₂-eq (SD=2833). During the KLiB project, households of the SWC type further increased air travel emissions on average by 845 kg CO₂-eq (SD=1938) per capita to a total of 3386 kg CO₂-eq (SD=2987). This is 33.3 % higher than the baseline average value, 5.8 times the German average, the largest growth in air travel emissions of all types and the second highest KLiB value. The highest emissions balance in air travel, though, shows the CWC type with 3724 kg CO₂-eq (SD=3760) which corresponds to an increase of 403 kg CO₂-eq (SD=4412) per capita, 12.1 % higher emissions compared to the baseline 2017. For comparison, the CWC type's absolute value in 2018 is approximately 6.4 times the German average. The CNC type shows the third highest air travel emissions in both baseline and KLiB emissions balances. While in 2017 households of the CNC type marked emissions of 1645 kg CO₂-eq (SD=2848) in average, they exceeded that value by 557 kg CO₂-eq (SD=2368) to a total of 2212 kg CO₂-eq (SD=3535) per capita. This is the second highest growth in absolute figures, with 34.5 % being the highest

increase compared to the own baseline and approximately 3.8 times the German average.

The FNC type is the only type whose households in average managed to reduce emissions within the domain of air travel. Revealing just a slightly lower baseline balance than the CNC type with 1615 kg CO₂-eq (SD=2753), however, the FNC type's emissions decreased in 2018 by about 96 kg CO₂-eq (SD=3292) to 1519 kg CO₂-eq (SD=1963) per capita. This is 6 % less emissions in relation to the baseline but still 2.6 times the German average. The FWC and SNC types show the lowest baseline and KLIB emissions balances and are close to each other for both respective values. Nevertheless, both types record increased emissions in 2018. The FWC type with marginally higher baseline emissions of 1193 kg CO₂-eq (SD=955) states a growth of 297 kg CO₂-eq (SD=1566) to a total of 1490 kg CO₂-eq (SD=1459). This corresponds to an increase in emissions of 24.9 % compared to the baseline year 2017 and is approximately 2.6 times the German average. The SNC type has in fact lowest emissions balances of all types. The baseline emissions balance of 1157 kg CO₂-eq (SD=2159) is somewhat lower than the FWC type's, but was exceeded by 215 kg CO₂-eq (SD=1685) in 2018 and therewith totaled 1372 kg CO₂-eq (SD=3714) per capita. Despite the emissions increase it is the lowest air travel emissions balance of all six types for the KLIB year. Nonetheless, it is still 18.6 % higher than its own baseline value and approximately 2.4 times the German average.

Interestingly, in air travel as in ground mobility the single and couple car-owning household types exhibit distinctly higher per capita emissions compared to their counterparts without cars. The family types, however, show approximately similar values, at least for the KLIB year 2018. In the context of air travel, it is important to note that of the total sample analysed here (n = 63), 22 households did not fly at all during the KLIB year 2018, which proportionately corresponds to 34.9 % of the sample. For an overview on descriptive statistics dispersion and location parameters of the baseline and KLIB emissions variables (cf. *Figure 24*) as well as the difference variables

(cf. *Figure 25*) of air travel per household type see appendix B (cf. *8 Appendix B*), which provides the corresponding boxplots.

4.5 Comparison of ground and air travel emissions – total emissions balancing

As already mentioned in subchapter 4.4, two opposing trends in the emissions trajectories of ground mobility and air travel are striking: in ground mobility all household types consistently showed emissions well below the German average of 1.600 kg CO₂-eq per capita for the project year 2018 and, except for the SWC type, also for the baseline year 2017 (cf. *Figure 5*). In air travel, the exact opposite is the case. All household types reveal emissions at least twice as much the German average of 580 kg CO₂-eq per capita for both the baseline and KLIB year, partly distinctly higher (cf. *Figure 18*). Also in direct comparison of the mobility segments, all six household types show clearly higher emissions values in air travel than in ground mobility for the baseline and KLIB year. Furthermore, while in ground mobility five out of six household types show decreased emissions balances for 2018, it is the other way round in air travel. Here, distinct emissions increases can be observed for again five out of six types (cf. *Figure 5, Figure 18*).

Figure 19 finally presents the total emissions balances of the baseline and KLIB year per household type integrating emissions of ground mobility and air travel. It is immediately noticeable that for the five types (SWC, SNC, CWC, CNC, FWC) that showed strong emissions increases within air travel, emissions reductions of ground mobility were thwarted and overcompensated. Thus, an overall increase in total emissions is can be determined for these types, even if only slightly in some cases.

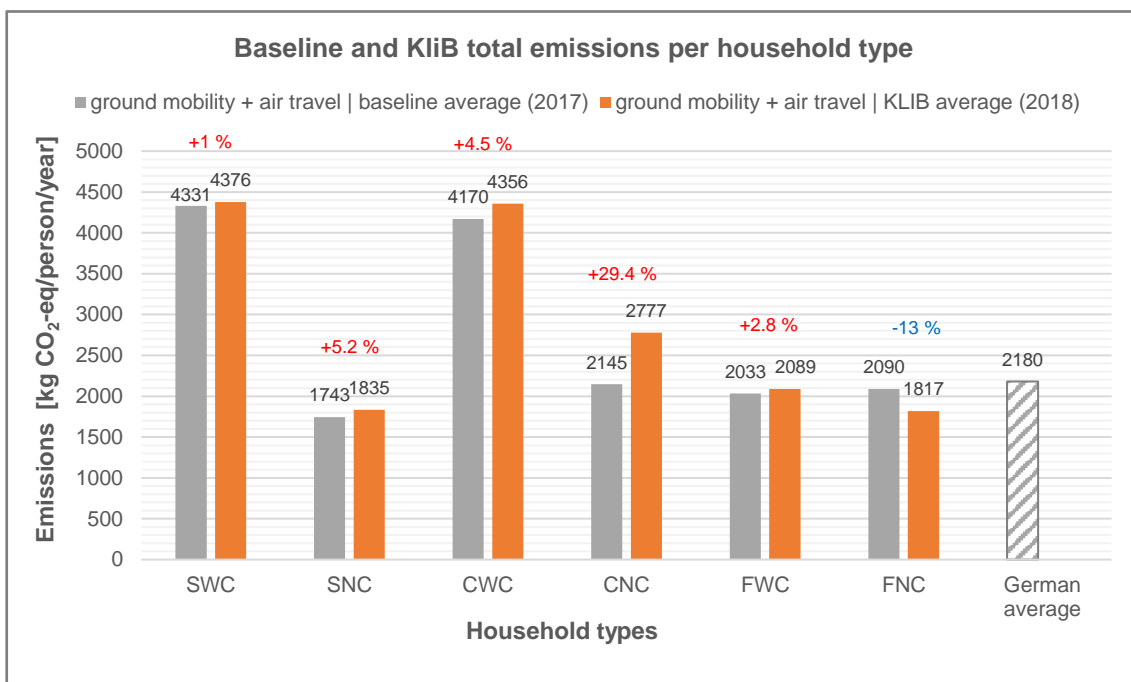


Figure 19: Baseline (2017) and KLiB (2018) average total emissions [kg CO₂-eq/person/year] of ground mobility and air travel per household type in comparison with German average (2180 kg CO₂-eq/person/year). Total values are presented directly above bars. Relative differences of KLiB performance in relation to the baseline are shown above bar couple per type in percentage: reductions (blue) or increases (red).

The only household type that has effectively managed to reduce total emissions during the KLiB project within the domain of mobility is the FNC type (cf. Figure 19). It was also the only type to reduce emissions particularly in air travel as well as in ground mobility. Baseline total emissions of the FNC type are 2090 kg CO₂-eq (SD=2824) per capita. In 2018 total emissions were reduced by 273 kg CO₂-eq (SD=3410) to a total of 1817 kg CO₂-eq (SD=2062) per capita. This corresponds for 13 % less emissions compared to the baseline and is the lowest total emissions balance for 2018 of all household types. Moreover, the emissions balance is clearly below the German average of approximately 2180 kg CO₂-eq per capita and year for ground mobility and air travel combined.

In addition to the FNC type, the FWC and SNC types are also below the combined German average in both years despite the overall slight emissions increases. Yet it is interesting to note that these three types were already below the German average in the baseline year 2017. The FWC type's baseline emissions balance is with 2033 kg

CO₂-eq (SD=1049) per capita somewhat lower than the FNC's. But emissions increases in air travel outweigh reductions in ground mobility, leading to an overall slight increase of 56 kg CO₂-eq (SD=1611) per capita. Therefore, emissions totaled 2089 kg CO₂-eq (SD=1481) per capita in 2018 which are 2.8 % more emissions than in the previous year. The SNC type shows the lowest total baseline emissions with 1743 kg CO₂-eq (SD=2042) per capita. Though, overall emissions increased by 92 kg CO₂-eq (SD=1845) and therewith exceeded the baseline balance by 5.2 % to a total of 1835 kg CO₂-eq (SD=3674) per capita in 2018. Despite the emissions increases the SNC's total KLIB balance is just marginally higher than the FNC type's KLIB balance. The total baseline balance of the CNC type was with 2145 kg CO₂-eq (SD=2817) per capita just below the German average in 2017. Due to the distinct emissions increases in both ground mobility and air travel (cf. *Figure 5*, *Figure 18*) of in total 632 kg CO₂-eq (SD=2554) per capita, however, the total emissions balance of 2777 kg CO₂-eq (SD=3810) per capita clearly exceeded the German average in 2018. With respect to the own baseline balance this corresponds for 29.4 % higher emissions. In this respect, the CNC type represents somehow the counterpart of the FNC type, being the only type revealing emissions growths in both mobility segments and thereby the largest total emissions increase of all household types.

The CWC type's total baseline emissions totaled 4170 kg CO₂-eq (SD=5867) per capita with about 80 % just related to air travel. Notwithstanding this, air travel emissions increased distinctly in 2018 (cf. *Figure 18*), negating emissions reduction efforts in ground mobility and led to an overall increase of 186 kg CO₂-eq (SD=4335) to a total of 4356 kg CO₂-eq (SD=3631) per capita. This corresponds for a 4.5 % higher total emissions balance compared to the baseline 2017 and approximately two times the German average. In direct comparison of total baseline and KLIB emissions balances of the SWC type there is not much of change observable. However, as already identified in the detailed analysis of the individual mobility segments, the SWC type is the one of opposing extremes: it is the type with highest absolute emissions reductions in ground mobility (cf. *Figure 5*), but the other way round also the one with greatest absolute emissions increases in air travel (cf. *Figure 18*). In the end, emissions

increases overcompensated for the reductions here as well, even if only slightly. The baseline balance of 4331 kg CO₂-eq (SD=3095) was exceeded by 45 kg CO₂-eq (SD=1810) and therewith totaled 4376 kg CO₂-eq (SD=2919) per capita in 2018. It is only 1 % higher than the baseline balance, but the highest per capita value of total emissions of all types, two times the German average (2180 kg CO₂-eq per capita) and 2.4 times the lowest balance of the FNC type.

If one allocates to the individual modes of transport their respective emissions shares for the KLIB year 2018 and presents them by household type, as illustrated in *Figure 20* (relative) and *Figure 21* (absolute), it can be clearly recognised that air travel consistently accounts for the largest share of emissions across all types. Air travel caused more than 70 % of total mobility related emissions among all household types.

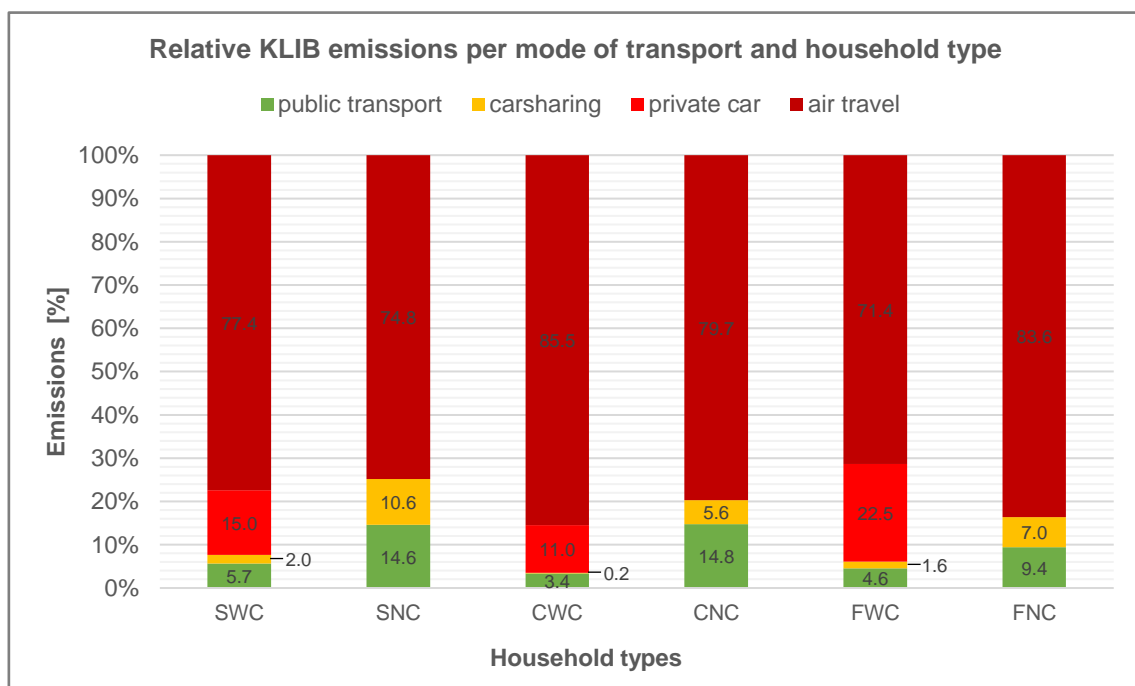


Figure 20: Relative KLIB (2018) emissions [%] per mode of transport (public transport, carsharing, private car, air travel) and household type. Relative values per mode are presented within bars sections and partially beside (carsharing) for a better visibility.

For the CWC type with the largest absolute air travel emissions, they account for 85.5 %, and for the SNC type with the lowest absolute share, they still account for 74.8 % of total mobility emissions. If one takes the private car as the second largest source of mobility emissions as a comparison, the emissions of air travel are approximately

3.2 times higher for the FWC type, 5.2 times higher for the SWC type and 7.8 times higher for the CWC type (cf. *Figure 21*). Even if the emissions of all modes of ground mobility are added together, the emissions of air travel remain a multiple of this for all types. It becomes evident without reservation that the emissions of the other modes of transport are proportionally of little weight compared to those of air travel.

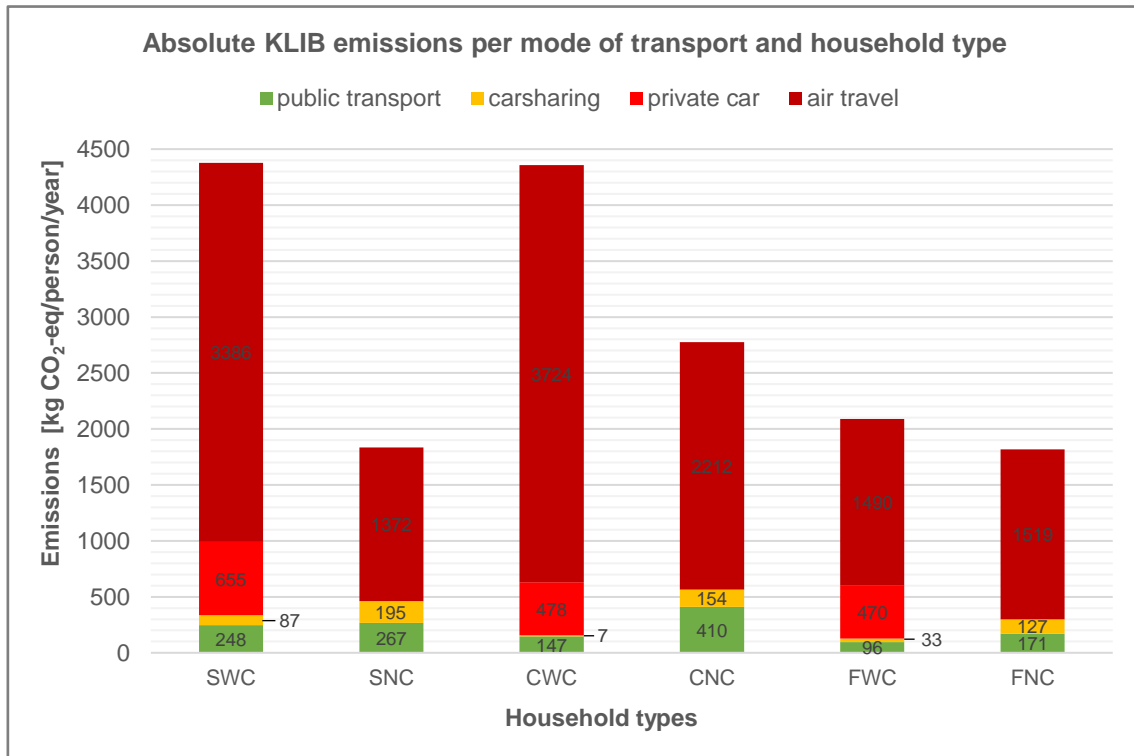


Figure 21: Absolute KLIB (2018) emissions [kg CO₂-eq/person/year] per mode of transport (public transport, carsharing, private car, air travel) and household type. Absolute values per mode are presented within bars sections and partially beside (carsharing) for a better visibility.

5 Discussion

I opened this study questioning to what extent different urban household types reduce mobility-related CO₂-eq emissions through voluntary action and changes in mobility behaviour towards low-carbon mobility forms and patterns within a real-world lab experiment (KLIB). In the following, the results of this study will be interpreted, related to the research questions and discussed accordingly in the context of the research background (cf. chapter 2) and further relevant literature. Subsequently, the methodological limitations are pointed out, evaluated in their relevance and influence on the results of the study and discussed respectively.

5.1 The opportunity window in everyday mobility

The ‘urban’ and ‘green bias’

The pattern that immediately stood out in connection with the results of ground mobility emissions shall likewise be discussed first, as the corresponding explanations also frame this study’s discussion: all types except the SWC type exhibit clearly lower baseline emissions balances within ground mobility than the German average from the outset (cf. *Figure 5*). This distinct pattern can to a large extent be explained by two decisive initial contextual conditions of the KLIB project. The urban context and the recruitment of households led to an ‘urban’ and ‘green bias’ of the sample, as already highlighted by Reusswig, Lass and Bock (2020). The contextual factors of the ‘urban bias’ relevant for this study relate to the structural framework conditions of spatial urban form and infrastructure as well as their effects on the mobility behaviour: urban households tend to have clearly lower direct emissions from transport than rural households. This is due to density effects like shorter ways, good conditions for active travel like walking and biking, a dense public transport network as well as better spatial accessibility through the latter (Lanzendorf and Hebsaker, 2017; Gill and Moeller, 2018; Oostendorp *et al.*, 2019). Ivanova *et al.* (2018) found that settlement density and the related effects are a key element for emissions reductions in the domain of ground mobility. The higher the settlement density in which a household is

located, the shorter the trips and the lower the mobility-related emissions (Ivanova *et al.*, 2018; Schelewsky, Follmer and Dickmann, 2020). The density effects are correspondingly stronger and more comprehensive in a metropolis like Berlin (cf. Schelewsky, Follmer and Dickmann, 2020, pp. 56 f.), which in turn may explain the significantly lower baseline ground mobility emissions of five out of six household types compared to the German average (cf. *Figure 5*).

In addition, as explained in section 2.5.1 (*Recruitment*), the recruitment of households entailed a form of 'self-selection', leading to a participation of predominantly committed people with an above average interest in climate change, environmental issues and carbon footprint reduction. The self-selection thus led to a 'green bias' of the sample at the attitudinal level with participating households already concerned about reducing their carbon footprint, e.g. in terms of mobility by using public transport or riding a bike (cf. Reusswig, Lass and Bock, 2020). However, this was anticipated in the research design and part of the voluntary character of the project. The participants should reduce their carbon footprint out of their own drive and motivation (cf. Reusswig, Lass and Bock, 2020). The 'green bias' may thus have additionally contributed to the lower baseline emissions from ground mobility compared to the German average. Correspondingly, for the further discussion it remains to be noted that the preconditions for reducing the mobility carbon footprint were relatively good, firstly due to the urban context and secondly due to a sample of environmentally aware and motivated participants. Equally important for the later contextualisation of the results is the higher proportion of mobile professional backgrounds of the participants (academics, executives etc.) (Reusswig *et al.*, 2021). The above-average share of middle net income classes within the sample (cf. section 4.1; Reusswig, Lass and Bock, 2020) also indicate that KLIB households were largely recruited from the urban 'educated middle class'.

Distinctive patterns along car ownership

It was shown that all household types except for the CNC type successfully reduced emissions within the domain of ground mobility. Nevertheless, there are clear differences observable between the types, prominently marked through two distinctive patterns which stood out along the characteristic of *car ownership*: firstly, the household types with cars (SWC, CWC, FWC) not only exhibit consistently higher baseline emissions than their counterparts without cars (SNC, CNC, FNC), but also show higher KLIB emissions throughout. And this, secondly, despite clearly higher absolute emissions reductions of the household types with car (cf. *Figure 5*). These distinctive patterns are initially discussed in the following, also considering the type-related different households living situations. First, some decisive developments regarding modal choice and transport demand are addressed, which led to the overall strong emissions reductions within ground mobility.

Modal shift in urban context

Synthesising and assessing the results on modal choice and transport demand (cf. section 4.3.2), a clear pattern emerges, albeit with type-specific differences: for all household types with car, a considerable reduction of car use in terms of transport performance can be noted (cf. *Figure 7, Figure 9, Figure 11*) as well as a reduction in the private car's modal share, prominently in favour of public transport (cf. *Figure 6, Figure 8, Figure 10*). Thus, there is a clear *modal shift* observable among all three types, away from the private car towards the public transport systems (cf. section 2.3.2, *modal shift*). In the case of the SWC type, there is even a slight shift in the direction of the bike discernible (cf. *Figure 6*). This overall modal shift is certainly accountable for a large part of the emissions reductions from the household types with cars within ground mobility. In this respect, the 'urban bias' again plays a decisive role: a modal shift towards low-carbon modes of transport like bike or local public transport systems is much easier in cities, particularly in large cities like Berlin. Urban households have more mobility options (inter- and multimodal), are therefore less dependent on

the private car and thus have more opportunities and a stronger lever for emissions reductions in ground mobility than households in more disconnected or rural regions (Kuhnimhof *et al.*, 2012; Lanzendorf and Hebsaker, 2017; Oostendorp *et al.*, 2019). This is reinforced by the fact that Berlin has one of the best public transport systems worldwide in terms of spatial accessibility and performance (rapidly connecting people and places) (Biazzo, Monechi and Loreto, 2019; Oostendorp *et al.*, 2019). The distinctly higher proportion of urban households without private cars, reflected by this sample (cf. section 4.1), compared to the proportion in more rural regions also demonstrate these multimodal effects and urban contextual factors (Nobis and Kuhnimhof, 2018, pp. 34 f.).

In addition, households of the FWC type in particular substantially reduced their total transport performance (cf. *Figure 11*). The CWC households reduced it as well, albeit to a much lesser extent (cf. *Figure 9*). This consistently leads to further strong reductions in emissions, since a non-occurring trip also causes no emissions. In contrast, SWC households actually increased their total transport performance distinctly (cf. *Figure 7*). Furthermore, the reduction in private car transport performance relative to the baseline was comparatively smaller for the SWC type than for the other two types. These circumstances explain in practical terms why the SWC households, despite the distinctive modal shift and largest total emissions reductions, nonetheless exhibit the highest KLIB emissions balance in ground mobility of all six types.

Carbon lock-in through car ownership

The KLIB modal splits of the car-owning types, nevertheless, also indicate that despite the modal shifts, the private car consistently remains an important mode of transport with still considerable modal shares (cf. *Figure 6, Figure 8, Figure 10*). This is certainly the reason why, despite the partly considerable emissions reductions, none of the household types with a private car achieved a lower KLIB emissions balance than any of the car-free types. This can be considered as further evidence for the path dependency or *carbon lock-in* effects related to *car ownership*, in accordance with preceding

explanations and other studies referenced (cf. section 2.2.4, *carbon lock-in of car ownership*; Jones and Kammen, 2014; Erickson *et al.*, 2015; Seto *et al.*, 2016; Ivanova *et al.*, 2018). The conventional (internal combustion) car is the strongest carbon lock-in of private households due to associated social norms and supporting infrastructure (Seto *et al.*, 2016). Those who own a car also use it. On the one hand, this is due to the 'technological lock-in', the path-dependent binding by the actual ownership (in terms of possession) and the associated 'sunk costs' (as well as embedded emissions) through the acquisition (Seto *et al.*, 2016). Accordingly, there is an economic incentive to use the car once it has been purchased. In this context, Erickson *et al.* (2015) found that once bought, it would require a very high carbon price (>1000 \$ per t CO₂) to displace an internal combustion car out of economic incentives alone. On the other hand, there are also 'behavioural lock-in' effects that are interrelated with the technological one, which can counteract a motivation to change behaviour that is f.i. grounded by environmental awareness or socio-ecological intentions (Seto *et al.*, 2016). Travel habits or routines limit the information needed in recurring everyday mobility to make decisions about how to reach a destination, i.e. also by which mode of transport (cf. Aarts, Verplanken and van Knippenberg, 1997; Busch-Geertsema *et al.*, 2016, p. 766). This reduction of complexity in repetitive everyday mobility situations frees up cognitive capacities for other activities, such as listening to the radio while driving (Busch-Geertsema *et al.*, 2016, p. 766). This in turn can lead to synchronic habits that reinforce the mode choice and car-using habit (Brette *et al.*, 2014). Accordingly, it is unsurprising that private car users are more affected by their travel habits than public transport users (Donald, Cooper and Conchie, 2014). As a consequence, the private car is usually so firmly integrated into everyday mobility, travel habits and social routines of car owners that it can be very difficult to completely do without it (cf. Rosenbaum, 2016, pp. 551 ff., 563), even if there is a profound attitudinal motivation to do so.

If *car ownership* or respectively the renunciation of car ownership is considered as an additional criterion of the participants' environmental determination, the KLIB sample could also be regarded in a more differentiated, gradual way: the 'environmentally

determined' household types which consistently refrain from using a private car and a graded variant of 'environmentally aware' household types who are aware of the environmental and climate impact of car use and are also committed to change their mobility behaviour, but are not willing or able to completely refrain from using a private car (cf. Rosenbaum, 2016, p. 563; Scheiner, 2016, p. 694).

The low-cost hypothesis

Environmental sociological research has revealed that environmental awareness and attitudes only have an influence on behaviour to a certain extent (cf. Preisendörfer and Diekmann, 2012, pp. 1210 f.). Transport research comes to a consistent conclusion in this respect – environmental attitudes do not necessarily match with mobility or travel behaviour (Susilo *et al.*, 2012). A key explanation for this discrepancy is provided by the *low-cost hypothesis* (cf. Diekmann and Preisendörfer, 1998, 2003) derived from rational-choice theory: accordingly, the influence of environmental awareness and attitudes on action and behaviour depends on the costs associated with that behaviour – the *behavioural costs* – whether these are monetary costs, convenience costs, time costs or costs in the form of behavioural effort (cf. Diekmann and Preisendörfer, 1998, 2003; Preisendörfer and Diekmann, 2012, pp. 1208 f., 1210 f.). The strength of the effects of environmental attitudes on behaviour thus depends on the cost intensity of the situation. In 'low-cost situations', environmental awareness has a strong effect on action; in 'high-cost situations', it has only a weak effect (Diekmann and Preisendörfer, 2003). Therefore, environmental awareness and attitudes influence behaviour primarily in situations and under conditions that are related to low behavioural costs. However, transport and mobility behaviour are usually typical high-cost domains (Diekmann and Preisendörfer, 2003). These high-cost decision situations concern, on the one hand, within everyday mobility, especially car use versus its low-carbon alternatives (e.g. local public transport, bike). On the other hand, they apply in the holiday and long-distance travel context to car and air travel versus long-distance rail travel (cf. Diekmann and Preisendörfer, 2003). In these contexts, the behavioural costs (related to convenience, comfort, privacy, safety, independence, etc.;

cf. section 2.3.3) in the logic of utility maximization within a mobility decision situation are perceived relatively high by car drivers concerning a modal shift (cf. Diekmann and Preisendörfer, 2003). In addition, the environmental determination of car-owning households might be weaker, so that counteracting behavioural costs more easily outweigh in the hypothetical mobility decision situation.

There are thus technological and behavioural carbon lock-in effects, as well as potentially higher perceived behavioural costs for the car-owning household types than for the car-free ones, which may have counteracted the extent of change in mobility behaviour and would consequently explain the distinct differences in the emissions balances.

KLIB as a 'window of opportunity' for behavioural change

However, after all, one thing is indisputable: all household types (except for the CNC type) and in particular those with private cars, have achieved considerable emissions reductions compared to the German average (cf. *Figure 5*) within ground mobility. How can these reductions be explained with respect to behavioural changes and their emergence in everyday mobility – also with respect to the cited barriers in the form of travel habits, technological and behavioural carbon lock-ins?

In this regard, the real-world lab experiment KLIB as a setting for (social-dynamically reinforced) 'context change' and motivation driver for behavioural change is of relevance. If the behavioural context changes – in relation to the physical, spatial environment with urban form and infrastructure as well as temporal and social factors that influence behaviour – it is possible to break up the routinised behaviour of travel habits from everyday mobility (cf. Verplanken *et al.*, 2008). In this case, decisions are again made more consciously and with the inclusion of additional information. A 'window of opportunity' of increased attention is created, in which behaviour-influencing interventions like information and communication strategies can be used to bring about changes in behaviour before new routines adapted to the changed circumstances are established (cf. Verplanken *et al.*, 2008; Busch-Geertsema *et al.*, 2016,

pp. 767 f.). If one takes the contextual factors of urban form and transport infrastructure of Berlin (density effects, inter- and multimodal mobility options), like described above, as basically good preconditions for behavioural-related emissions reductions in mobility (through e.g. modal shift or modal avoid), the socio-contextual factors that are also decisive for triggering behavioural change remain. These contextual factors were influenced and modified by the KLIB project and its objectives: through the 'experimental space' of the RwL (to try out new), the interventions like the *carbon tracker* and the low-carbon mobility tips (motivation guided by carbon feedback and information) as well as through the social-integrative but also social-comparative character of the project in terms of 'trying out together' (live meetings, forum discussions, carbon footprint benchmarking etc.) (cf. section 2.5.1, *Interventions*; Reusswig, Lass and Bock, 2020).

The RwL experiment KLIB changed the context of action for the participating households through 'external triggers' and thus led to a 'window of opportunity' for behavioural changes. The clear goal of reducing emissions set the scope and direction for action and behaviour. The carbon tracker provided constant feedback and information on the impact of their actions on the household carbon footprint (e.g. how much CO₂-eq is caused through the daily commute by car) as well as social comparison and referencing through the carbon footprint benchmarking with the other households. The low-carbon mobility tips (cf. *Table 1*) provided information on effect weighted action options to reduce emissions in the domain of mobility, clearly targeting and promoting modal shift and modal avoid strategies and measures (cf. section 2.5.1, *Interventions*). Other studies from the energy domain have already demonstrated that goal setting and tailored information and feedback instruments can significantly contribute to energy and CO₂-eq reductions of households (cf. Abrahamse *et al.*, 2007; Ehrhardt-Martinez, Donnelly and Laitner, 2010; Delmas, Fischlein and Asensio, 2013; Harries *et al.*, 2013). Furthermore, social comparison and normative referencing and feedback with the other participating households (through the live meetings, carbon footprint benchmarking, forum discussions etc.; cf. section 2.5.1, *Interventions*) could have additionally contributed to reinforce motivation, the ambitions and persistence

of behavioural changes in ground mobility (cf. Allcott and Rogers, 2014; De Dominicis *et al.*, 2019). When participants perceive themselves as socially embedded actors in a group instead of isolated individuals, social comparison and normative referencing within that group can lead to the re-negotiation of existing social norms and the emergence of new ambitious norms for practice, in this case for low-carbon mobility practice (cf. De Dominicis *et al.*, 2019; Bamberg, Rollin and Schulte, 2020; Ruhrort and Allert, 2021).

The KLIB Rwl experiment thus constituted a *key event* for behaviour change (cf. section 2.3.3), founded on good spatial-contextual preconditions in terms of urban form and infrastructure ('urban bias'), an initial pro-environmental motivation ('green bias') and induced and supported by targeted interventions (cf. Scheiner, 2007; Busch-Geertsema *et al.*, 2016, pp. 767 f.). The 'window of opportunity' created by the 'context change' was leveraged to bring about the intended change in mobility, with corresponding different results depending on the household types and their living situations.

The effects of household living situation and household size

Yet how can it be explained that family households consistently achieve the lowest emissions balances in ground mobility within the main groups (car-owning and car-free types)? Why do the couple households and then the single households follow with the highest emissions balances within the car-owning household types? It is plausible that this pattern (except for the outlier type CNC) is attributable to the household living situation and the household size.

A recent study based on the large-scale mobility study series MID determined the CO₂ footprint of German households in everyday transport. It revealed that with an increasing number of persons in a household, the specific per capita emissions decrease (Schelewsky, Follmer and Dickmann, 2020). This can be explained on the one hand by shared trips, where the per capita emissions decrease due to a higher occupancy of vehicles, e.g. in the case of private car or carsharing (cf. section 2.1.2 and 2.3.2,

Improve) – and on the other hand by the fact that certain recurring trips are only performed once per time interval for the entire household, e.g. the weekly household grocery shopping (cf. Schelewsky, Follmer and Dickmann, 2020). It is clearly more way- (in terms of trips) and CO₂-efficient to conduct one large grocery shopping trip for three or more people as if each person would drive alone, like it is the case for single households. Furthermore, in a family household, it is often possible to synchronise trips spatially and temporally, e.g. by driving the children together to school and afterwards to work. Parents' drop-off and pick-up services might be combined into one trip, which increases the occupancy rate of vehicles and simultaneously reduces the number of trips. The higher occupancy rate of vehicles as well as the overall reduction of trips through a more efficient trip management can therefore contribute considerably to the reduction of emissions for multi-person households in the mobility domain (Schelewsky, Follmer and Dickmann, 2020; Allekotte *et al.*, 2021). These emissions-reducing effects of trip sharing, reduction of (recurring) trips and trip combination occur to a correspondingly lesser extent in couple households and barely in single households, which in turn may explain the according gradation of the per capita emissions balances of the household types.

The leverage effect of car renunciation and best-practice

If the baseline emissions from ground mobility are already relatively low, it is consequently more difficult to reduce them proportionately strongly. It is all the more remarkable that one household type demonstrates just that. The FNC households reduced their emissions relatively compared to their own baseline emissions the second most after the SWC type, thus achieving the lowest absolute KLIB emissions of all household types (cf. *Figure 5*). The FNC type already showed the lowest baseline emissions, even though two households recorded a private car in 2017 and also drove it. These two households must have sold their car before the 2018 observation period or at least not used it (cf. *Figure 16*). The relatively strong emissions reductions of FNC households are thus amongst others attributable to the leverage effect of the complete renunciation from car use by these two households. In consideration of the

previously made distinction between ‘environmentally determined’ and less resolute ‘environmentally aware’ household types, these findings are interesting to frame. In this perspective, KLIB as a key event may have triggered a strategically effective decision and behavioural change: the window of opportunity was seized to dare a complete shift of household mobility to low-carbon modes, and with success. One could assume that the ‘context change’ of the RwL experiment also entailed an increase in ‘ecological determination’ in terms of actions. Possibly the motivation to abandon the private car was already there beforehand, it only needed a trigger to put it into action.

In addition, these are family households with children, for whom a shift to alternative modes of transport could be more difficult operationally than for example single households. It can be assumed that in family households, the private car is even more integrated into processes and routines of everyday mobility than in single or couple households, if only because more people rely on it due to their social practices. In connection with work, shopping and provisioning, accompanying and caring for children as well as leisure activities of individuals and the whole family, the car usually plays an important role (cf. Rosenbaum, 2016, pp. 564 ff.). Nevertheless, car-free mobility seems feasible even for families, at least in a city like Berlin with a strong public transport system (cf. Biazzo, Monechi and Loreto, 2019; Oostendorp *et al.*, 2019), as convincingly demonstrated by the largest group within this sample, the FNC type (cf. *Table 2*), while simultaneously reducing emissions. The second largest group of households, the FWC type, is on similar track with strongest absolute reduction in the private car’s transport performance (cf. *Figure 11*) and lowest KLIB emissions of the car-owning household types (cf. *Figure 5*).

A surprising pattern was that four out of six types recorded a decreased bike transport performance during the observation period 2018 despite the intended emissions reductions. This is astonishing in the respect that the bike as a carbon-neutral transport alternative has good preconditions in the dense infrastructure system of a city like Berlin. It is even the fastest and most cost-efficient means of transport for short distances under 5 km (with considerable CO₂-eq savings potential compared to the

private car) (cf. section 2.3.2, *Shift*; UBA, 2021f). The participating households were informed about these facts (cf. *Table 1*). Given the KLIB target, these facts and preconditions, why would the households bike less than they did before? Therein lies a clear contradiction. However, it is likely that this contradiction is of methodological origin and related to the lump-sum retrospective estimates of the households for the baseline survey (cf. section 3.1.2, *Baseline survey version*). Accordingly, it will be addressed in the methodological limitations of this study.

5.2 The air travel paradox

The domain of air travel delivered contradictory results with regard to the intended objective of reducing emissions and against the background of the environmentally aware and committed, 'green' sample of participants. In the context of air travel, two completely opposite trends to ground mobility emerged: firstly, while in ground mobility all types exhibited emissions far below the German average in 2018 (cf. *Figure 5*), in air travel they are consistently well above the German average (cf. *Figure 18*). For both the baseline and the KLIB year, emissions were at least twice as much as the German average, partly considerably higher. **Secondly**, while in ground mobility five out of six household types reduced emissions in 2018, it is the other way round in the domain of air travel. Here, distinct emissions increases can be observed for again five out of six types (cf. *Figure 5*, *Figure 18*). Thus, in contrast to the German average, all six household types show clearly higher emissions values in air travel than in ground mobility for both the baseline and KLIB year. Ultimately, the emissions increases in air travel for the five types (SWC, SNC, CWC, CNC, FWC) were so strong that the partly substantial reductions in ground mobility were thwarted and overcompensated (cf. *Figure 19*).

One could assume or argue that the results of air travel emissions are influenced by the methodological approach of averaging by type, as the arithmetic mean is sensitive to outliers and air travel is particular emissions-intensive. So one could speculate, exaggeratedly expressed, that there were some very mobile, frequently flying participants within the household types that distorted the overall results and possibly the

majority did not fly at all during the KLIB observation period. Indeed, there were a few outliers within some types that caused more air travel emissions than the rest of the households, but especially in these types with comparatively lower average per capita emissions as the corresponding boxplots reveal (SNC, FWC, FNC; cf. *Figure 24*). At the same time, there was also at least one household in each type that did not fly at all during KLIB. In fact, however, these households were consistently in the minority – another differentiated examination of the entire sample concordantly confirmed the clear trend with regard to air travel: of the 63 households, 22 did not fly at all during the 2018 observation period. This corresponds to a ‘non-flyer rate’ of 34.9 % (cf. section 4.4). For comparison, a German aviation lobby organisation indicates in a representative survey that 56.8 % of respondents have not flown in the last two years (before the KLIB project) (BDL, 2018), while the opinion research institute IfD Allensbach (2020) found that 65 % of the German population had not flown in the last 12 months (reference 2019, thus during/after the KLIB project). Both sources indicate a clearly higher proportion of ‘non-flyers’. Furthermore, it may be relevant to emphasise that the respondents in these surveys did not have the clear intention to reduce their carbon footprint. Against this backdrop, the share of non-flyers among the KLIB households appears to be relatively low.

Lastly, a detailed breakdown of emissions by mode of transport revealed that air travel was by far the strongest emissions driver within all household types in the KLIB year 2018: air travel accounted for more than 70 % of total mobility emissions among each of the six household types (cf. *Figure 20*).

In the light of these results, the inevitable question arises how it can be explained that five out of six household types of a committed group of participants with an above-average interest in climate and environmental issues, with the intention of reducing emissions, equipped with information and feedback on the climate impact of air travel (cf. section 2.5.1, *Interventions; Table 1*), nevertheless do not manage to reduce emissions from air travel, but on the contrary increase them considerably in

some cases? Furthermore, why do they manage to successfully reduce emissions in everyday ground mobility, but predominantly fail to fly less?

The environmental attitude–behaviour gap in holiday travel

Barr *et al.* (2010) found that environmental attitudes can be an important factor in transport choices for everyday mobility, but not for holiday travel. Individuals committed to environmental protection (based on attitudinal variables) reported environmentally friendly behaviours at home and in everyday life, however, transferring these practices to holiday contexts was problematic. This was particularly the case for emissions-intensive activities such as low-cost air travel: even those most committed to environmental issues and fully aware of the climate impact of air travel were not willing to fly less in the context of holiday travel. However, they were willing to accept taxes to mitigate this problem (Barr *et al.*, 2010). Barr and Prillwitz (2012) came to similar results when they examined the differences in transport mode choice for everyday, leisure and holiday travel in connection with climate change and sustainability. They found that behavioural changes involving a *modal shift* to low-carbon transport were much less accepted in the holiday and leisure context than in everyday mobility. Although respondents claimed environmental concern and commitment and perceived climate change as a threat, they were still less willing to avoid the emissions-intensive air travel, when they went on holiday (Barr and Prillwitz, 2012). Thus, both studies show that environmentally aware mobility behaviour is context-specific and usually adapted to everyday mobility practices and routines and therefore will not be consistently transferred to another context like the holiday trip (Barr *et al.*, 2010; Barr and Prillwitz, 2012). Behaviour is too inconsistent across social contexts for environmental awareness and associated values to be transferred from the home context to the holiday context. Cohen, Higham and Reis (2013), among many others (cf. also: Hares, Dickinson and Wilkes, 2010; Hergesell and Dickinger, 2013; Hibbert *et al.*, 2013; Kroesen, 2013; Juvan and Dolnicar, 2014), confirm these results of an *attitude–behaviour gap* in the context of holiday travel especially with respect to air travel. Furthermore, they point out that holiday transport is a particularly

challenging context for behaviour change, as western social imaginaries associate the spaces and contexts of holidays with casualness, relaxation and the loosening or complete abandonment of everyday social norms (Cohen, Higham and Reis, 2013). They consider holiday contexts and tourism practices as 'liminoid spaces' of different social identities (Cohen, Higham and Reis, 2013; cf. also Hibbert *et al.*, 2013).

Reusswig *et al.* (2021) showed in a second analysis of the KLIB project regarding the temporal development of emissions that household air travel was mainly related to public holidays. Thus, holidays represented a different spatial and social context in which the newly established, low-carbon mobility practices and routines of everyday life no longer worked for the KLIB households and in which environmental values, attitudes and intentions also had likely less influence on their travel decisions and mobility behaviour.

A particular 'high-cost decision situation'

The low-cost hypothesis is consequently also of explanatory relevance in this relationship. Holiday travel decisions represent a typical 'high-cost situation' in terms of *behavioural costs* (cf. Diekmann and Preisendörfer, 2003). That means, choosing a low-carbon transport alternative instead of the car or plane for travel (modal shift) is perceived to be such cost-intensive that environmental awareness and attitudes lose out. The results of Hergesell and Dickinger (2013) indicate that in this decision-making situation financial and time costs, followed by convenience, are of particular relevance. However, alternatives to air travel are often associated with contextual barriers that are perceived as high, such as financial, time, or comfort costs, and thus behavioural costs which counteract a modal shift (cf. Diekmann and Preisendörfer, 2003; Hergesell and Dickinger, 2013). This may be especially the case in times of low-cost air travel compared to higher-cost rail tickets (cf. Gössling, 2021). For instance, a journey to another country by plane is usually much faster, cheaper and more comfortable than by land or sea. The extreme example is the trip to a remote island or country: even ambitious environmentalists with intentions to reduce their carbon

footprint would probably take a plane instead of spending several days or weeks on a ship for the passage. In addition, as indicated above, there are symbolic and emotional values in the holiday context such as casualness, relaxation and the desire to compensate and reward oneself for the work and privations of everyday life (cf. Murtagh, Gatersleben and Uzzell, 2012; Cohen, Higham and Reis, 2013; Higham *et al.*, 2013).

The moral-licensing-effect

In terms of compensatory reward, indirect psychological *rebound effects* could additionally have played a decisive role (cf. section 2.3.2). A recent study just confirmed via a comprehensive survey analysis the connection between the attitude-behaviour gap and the existence of moral-licensing within travel decision-making (cf. Nikolić *et al.*, 2021). The *moral-licensing-effect* describes an indirect form of the rebound effect where the purchase and consumption of ecological or sustainable products and services also increases the demand for environmentally harmful products or services, as a quasi-moral balance or compensation (Sanatorius, 2012). For example, the use of low-carbon means of transport, or the purchase of an emissions and energy-saving electric car can lead to more frequent holiday trips by air travel. The emissions or energy savings in everyday mobility are thereby perceived to justify occasional 'un-ethical consumption' in the form of air travel (Sanatorius, 2012). However, this often coincides with the missing quantitative awareness of the significantly higher carbon impact of air travel, which may eventually lead to overcompensation of emissions savings and a considerably higher carbon footprint. An interview extract with one of the project participants illustrates this disadvantageous coincidence: "we have performed quite well this year in most domains. For example, it was a great help to have an energy consultant at our home,(...). Next to light bulb substitution, (...), he identified the fridge (...) to be the major driver of electricity consumption at home. We substituted it by a highly efficient new device and could immediately see how the tracker numbers went down! Together with many other small things (...), we've been quite successful and, yes, rather proud of being a 'good KLIB household'. All the more surprising was the fact that we jumped upward when our son went to New Zealand this year for a school exchange. This

'ate up' all the other savings—and left us a little frustrated. I didn't know how important air travel is!" (Male participant, 55 yrs, married, and a father of two children) (Reusswig, Lass and Bock, 2020, p. 431).

This sobering insight must have been experienced by some of the KLIB households in the domain of mobility. This is at least indicated by the air travel results of the five household types (SWC, SNC, CWC, CNC, FWC; cf. *Figure 18*), which increased their air travel emissions in the observation period 2018, in some cases considerably.

Nonetheless, there are also pronounced differences in the air travel emissions balances of the household types. Single and couple households with a car (SWC, CWC; cf. *Figure 18*) show the highest air travel emissions. One could assume that, as mentioned above, environmental values or 'environmental determination' for action are on average less pronounced in these households with regard to *car ownership* as an indicator. According to the low-cost hypothesis, the lower intensity of environmental attitude or determination could thus have less of an influence on behaviour particularly in such high-cost decision situations concerning holidays and air travel (cf. Diekmann and Preisendörfer, 2003). Barr *et al.* (2010) also found distinct differences across different lifestyle groups in terms of environmental attitudes, commitment and resulting intention for pro-environmental action and behaviour (cf. also Barr, Shaw and Gilg, 2011; Prillwitz and Barr, 2011; Barr and Prillwitz, 2014). The clear contrast to the SWC and CWC types is provided by the single households without a private car, which clearly show the lowest emissions balances in relation to air travel – possibly promoted by a stronger determination for environmentally friendly action. However, socio-demographic factors such as income and education are also likely to have played a role, as already outlined in section 2.2.4.

Income, education and cultural capital in the context of air travel

Relevant indications in this direction are provided by the insights of Reusswig *et al.* (2021) regarding the professional backgrounds of the participants. They found that the KLIB sample was largely recruited from mobile academics and executives with an

above-average share of middle incomes. In this respect, Ivanova and Wood (2020) demonstrated in comprehensive consumption data analysis of EU households how higher incomes in particular, but also the higher level of education, correlate with greater carbon footprints, especially with regard to air travel and land transport. Several studies have proven that income above a certain level and with increasing tendency is one of the strongest drivers of emissions in the domain of mobility, particularly air travel (cf. Aamaas, Borken-Kleefeld and Peters, 2013; Mieke *et al.*, 2016; Aamaas and Peters, 2017; Ivanova *et al.*, 2018; Dubois *et al.*, 2019; Ivanova and Wood, 2020). The income factor could in this connection also explain the relatively low emissions balances of the family types (FWC, FNC) compared to the SWC and CWC types. According to the disposable income determined on the basis of equivalence scales (cf. section 4.1, *equivalised disposable income*), family households have on average a significantly lower per capita *equivalised disposable income* than couple households in particular, but also than single households in Germany (Garbuszus *et al.*, 2018). Thus, with increasing number of children, the *equivalised disposable income* per capita decreases (Garbuszus *et al.*, 2018). Correspondingly, family households are on average poorer than specifically couple households without children. However, package holidays and air travel are luxury goods with a high energy and corresponding carbon intensity (Oswald, Owen and Steinberger, 2020), which family households can thus afford less of on average. Furthermore, with school-age children, they are more tied to public and school holidays. This in turn argues in favour of a few longer holiday trips (i.e. less air travel) rather than several short trips, as is conceivable among mobile single and couple households.

It was also shown that with increasing income, the average distance travelled increased and consequently so did the emissions (Ivanova *et al.*, 2018). The same applies to education: the higher the level of education, the greater the likelihood of travelling by air and the higher the carbon footprint (Minx *et al.*, 2013; Ivanova *et al.*, 2017, 2018). This is also specifically valid for the holiday trips of the Germans – the higher the educational level and the income, the greater the CO₂-eq emissions associated with holiday trips (Kleinhüchelkotten, Neitzke and Moser, 2016). A case study on German

travel behaviour found that the few trips beyond 100 km account for more than half of the total climate impact of travel, due to air travel (Aamaas, Borken-Kleefeld and Peters, 2013; cf. also Aamaas and Peters, 2017). This is indeed the case for each of the six household types in this study (cf. *Figure 20*). Furthermore, it was found in this context that couple households in Germany generate the highest per capita emissions related to holiday travel, which is exactly in line with the findings of this study regarding the CWC and CNC types within their respective main group (cf. Kleinhüchelkotten, Neitzke and Moser, 2016; *Figure 18*). Overall, all these findings are consistent with those of this study. Long-distance travel by air or several air travel trips per year are common among the educated middle classes with an above-average income (cf. Kleinhüchelkotten, Neitzke and Moser, 2016; Gössling *et al.*, 2017). To return to the example of the KLIB interview previously quoted: a household with a lower level of education and correlated less financial possibilities might go on holiday abroad once a year; but going on a student exchange to New Zealand or taking intercultural city trips to Marrakech, Istanbul, etc. for the weekend is something that is mostly done by households from the upper well-educated middle class (cf. Aro, 2016; Kleinhüchelkotten, Neitzke and Moser, 2016; Gössling *et al.*, 2017). Gössling *et al.* (2017) find in this context for Germany that a smaller highly mobile population group with higher formal education and an above-average household income undertakes five or more holiday trips per year. The most frequently cited reasons within this group were related to the exploration of new countries for new impressions and the discovery of something different as well as cultural or educational reasons (Gössling *et al.*, 2017). These travellers are also more likely to take the most carbon-intensive trips, such as those associated with long-haul flights (Gössling *et al.*, 2017). Larsen and Guiver (2013) likewise observe that bridging distances when travelling is linked to symbolic values and the experience of cultural differences. The high per capita emissions of the KLIB single (with car) and couple households could thus also be interpreted in this context. For both household types, travelling could play an important role as a form of cultural exploration and experience, intercultural exchange and education. Air travel is associated with the symbolic meaning of a cosmopolitan lifestyle and, in frequent form,

an expression of higher socio-economic status (Gössling *et al.*, 2017; Gössling, 2019). The possibility to be mobile is a form of ‘cultural capital’ (cf. Williams 2013). This mobility capital is certainly one of the strongest determinants of power in today’s societies. It is a privilege that one does not simply give up.

The social dimension of carbon inequality

When discussing the findings in relation to air travel, but also to overall transport, one eventually encounters issues that go beyond the KLIB dimension – issues of social inequality in mobility and, above all, a large social disparity concerning emissions, especially concerning air travel (Gössling and Humpe, 2020; Ivanova and Wood, 2020; Oxfam, 2020; ITF, 2021). This in turn is associated with social injustice, in the sense that the emissions’ ‘external costs’ (e.g. by causing climate change, air pollution, environmental degradation and biodiversity loss etc.) are still predominantly borne by society as a whole rather than by the polluters (cf. Maibach *et al.*, 2008; Preisendörfer and Diekmann, 2012, pp. 1206 ff.; Oxfam, 2020). The predominantly wealthy polluters do not bear the ‘external costs’ for the environmental or climate damage they cause, although they could afford to do so and would theoretically be also obliged to pay for it according to the *polluter-pays principle*²⁴ (cf. Biermann *et al.*, 2003; EC, 2021). The fact, that this problem has a relevant social dimension, in particular with regard to transport, is demonstrated by the findings of Ivanova and Wood (2020). Based on an analysis of socio-economic groups and their carbon footprints, they found that the top 10 % of EU households are accountable for 27 % of the EU’s carbon footprint, which is a higher contribution than that of the bottom 50 % of the population. The households with the highest carbon footprints are those with the highest income and expenditure and with the greatest carbon contribution from air travel and land transport. In this context, the top 1 % emit more than 22 times the 2.5-tonne 2030

²⁴ The *polluter-pays principle* is a guiding principle of environmental policy which states that the costs and control of environmental protection measures are to be borne by the polluter who causes pollution. Accordingly, the polluter must bear the ‘external costs’ of measures to reduce pollution according to the extent of the damage caused to society or the exceeding of an acceptable level of pollution (standards) (OECD, 2001; Biermann *et al.*, 2003).

carbon footprint target that would correspond to the 1.5 °C target (cf. section 2.2.3; IGES, Aalto University and Ltd., 2019), with air travel being the consumption category with the largest contribution (41 %) (Ivanova and Wood, 2020). Emissions inequalities between individuals and households are thus particularly apparent in the context of air travel, with significant implications for overall social justice (Gössling and Humpe, 2020; Oxfam, 2020; ITF, 2021).

5.3 Methodological limitations

5.3.1 Data collection limitations

The KLIB Rwl was, in line with its objectives, a broadly based research project that collected data from all domains of household consumption relevant to the carbon footprint. The strength in the breadth and comprehensiveness of data collection simultaneously led to weaknesses in the depth of detail of the mobility-related data, especially regarding the reference values of the baseline survey. Furthermore, the retrospective and subjective tracking or recording through the individual households created reliability issues, which, however, represent a general problem of data collection in transport research.

First of all, it should be emphasised once again that the KLIB households did not constitute a representative sample (cf. section 2.5.1, *Recruitment*; section 5.1, *The ‘urban’ and ‘green bias’*). This was also demonstrated by the comparisons with the German average. Therefore, the results are only transferable to a limited extent. However, as revealed during the discussion, environmentally aware, urban samples are not unusual within comparable studies on these topics. Moreover, the sample was not predetermined or constructed by the researchers, but was the result of the ‘random, self-selective sampling’ process (cf. section 3.1.1; section 2.5.1, *Recruitment*). ‘Green’ and ‘urban bias’ were deliberately accepted to ensure the voluntariness of participation, which was a clear component of the research design. After all, one of the main objectives was to find out to what extent voluntary behavioural changes can contribute to

the reduction of individual carbon footprints under existing policy and market conditions (cf. Reusswig, Lass and Bock, 2020; Reusswig *et al.*, 2021).

The *baseline survey version* disclosed some limitations in data collection for the mobility domain and an appropriate evaluation as required for this study. The mobility data for the reference year 2017 were retrospectively and individually estimated by the KLIB households on a lump-sum basis (cf. section 3.1.2, *baseline survey version*). The baseline survey was a requirement for participation in the project. Presumably to reduce the barriers to participation, a lump-sum version of the carbon tracker was used to collect the reference data. However, this had a clear influence on the mobility reference dataset generated and its comparability to the detailed RwL carbon tracker version. For instance, much fewer modalities were recorded, 'on foot' travel was completely disregarded, and public transport was only considered as a transport mode group and not differentiated according to the means of transport. Correspondingly, emissions were calculated using a statistically grounded average value of the transport mode mix (cf. section 3.1.2, *calculation principle*). It can be assumed that, at least in the domain of ground mobility, deviations from the actual emissions values occurred accordingly. However, as the results of this study (cf. *Figure 20*) and others have shown (cf. section 2.1.2, *figure 1, figure 2*; Allekotte *et al.*, 2020, pp. 121 ff.), it also can be expected that these deviations were hardly of any significance compared to the emissions of the private car. More problematic for the reliability of the data, is the fact that the households estimated their entire annual mobility patterns individually in retrospect – a retrospective, subjective estimation is detached from objective data collection. The same reliability problem applies to the individual tracking events of the weekly carbon tracker: each household in effect tracked itself. Even though the retrospective component is probably less relevant due to the weekly tracking, it still fails to be an objective data collection. The reliability of individual values and data must therefore be questioned.

Retrospectivity and subjectivity are, however, two characteristic problems of data collection within mobility or transport behaviour research. In general, it is very

difficult to reproduce mobility behaviour retrospectively in an empirically valid manner (Knie, 2016, pp. 37 f.). This in turn is related to the fact that mobility behaviour is shaped by habits and routines (cf. section 2.3.3). Since decisive actions in transport are shaped by routines, i.e. by habitual everyday actions, the level of attention and the proportion of consciously made decisions is low (Busch-Geertsema *et al.*, 2016, p. 766; Knie, 2016, pp. 37 f.). This is directly relevant for the collection of data on mobility behaviour, as respondents corresponding to the low attention or awareness of the transport decisions made, may not have detailed information on this either for themselves or for enquiries or surveys (Knie, 2016, pp. 37 f.). The annual distance traveled by private car can probably be reconstructed or assessed relatively validly using tools such as the odometer. However, it should be much more difficult to estimate retrospectively how much a person rode a bike or what distance was covered on foot over an entire year, and even possibly by several people within a household. Especially because walking and biking are mainly involved in the distance classes below 5 km (cf. Bracher, 2016, p. 271). Accordingly, the statistical database for foot and bike travel in general is relatively weak (Bracher, 2016, p. 271). In addition, in the specific case of the KLIB data recording of foot and bike travel, it might be relevant that the project was primarily concerned with emissions recording and reduction and not with mobility data collection. Accordingly, the carbon-neutral, active forms of transport, foot and bicycle travel, could have been (consciously or unconsciously) systematically neglected in the data collection.

These data collection problems also occur in the large German comparative mobility studies SrV (cf. Gerike *et al.*, 2020) and MID (cf. Eggs *et al.*, 2018; Nobis and Kuhnimhof, 2018), as these studies also work with 'reference date surveys' (cf. Eggs *et al.*, 2018). Due to the large number of respondents as well as the use of data preparation and cleansing methods, however, individual deviations and discrepancies of single cases are averaged out to a certain extent (cf. Eggs *et al.*, 2018). In order to counteract the aforementioned problems and limitations of data collection within transport research, this study accordingly attempted to reduce their influence by means of appropriate methods of data preparation (cf. section 3.2): input errors or data gaps due

to discontinuous tracking performance were addressed by data cleansing and correction using imputation (cf. section 3.2.2). The type formation counteracted the reliability problems of the retrospective self-tracking by the households: the data aggregation of the individual trips per mode of transport within the types, the contextual dispersion and outlier analysis (via standard deviation and boxplots) and in particular the consistent calculation of the arithmetic mean per mode of transport and all respective variables provided a certain quality assurance and strengthening of the validity of the data per household type. The application of the arithmetic mean to the aggregated variables of the individual households within a type was the principal method to establish comparability and achieve a certain levelling of questionable data from individual cases (cf. section 3.2.3 and 3.3.1).

Smartphone-tracking – an all-inclusive solution approach

A suitable technical solution to overcome the reliability issues of subjectivity and retrospectivity of data collection within mobility behaviour research is provided by smartphone-tracking (Schelewsky *et al.*, 2014). Smartphones are suitable and powerful data collection instruments that can, via suitable tracking applications, collect and present complex data precisely and objectively in approximately real time from a large number of cases and combined with direct analyses. Smartphones along corresponding tracking apps can use GPS to automatically record the intermodal routes of their owners and assign them to the respective means of transport used (Schelewsky *et al.*, 2014). It is even feasible to directly calculate the corresponding CO₂-eq emissions generated for each route or trip and means of transport. Combined, smartphone-tracking would increase the accuracy, reliability and level of detail of the data collected on complex mobility behaviour, facilitate data collection itself and simultaneously open up a wide range of new applications and research options. However, there are obstacles with regard to data protection and user acceptance of smartphone tracking, which must be addressed accordingly (Schelewsky *et al.*, 2014).

Carbon tracker versions

A more technical allocation limitation to the KLIB mobility data collection concerns the survey instrument, the carbon tracker, itself. The 2018 KLIB version of the carbon tracker only allocated the direct CO₂-eq emissions associated with the actual transport performance towards the mobility domain, but not for the embedded, upstream and downstream emissions of production, maintenance and disposal of vehicles like private cars. These embedded emissions were allocated to the domain 'other consumption' (Bilharz (UBA), 2020). However, a distinct share of total emissions related to MPT occurs in these areas (Allekotte *et al.*, 2020, pp. 55, 56 f., 121 ff.). The emissions allocation approach in this context has been updated in the new 2020 version of the carbon tracker: all indirect or embedded emissions, from production, maintenance and disposal of vehicles are now also allocated to the mobility domain (Bilharz (UBA), 2020). Considering the updated allocation or accounting approach of embedded emissions from vehicles, it can be reasonably assumed that the total emissions in the ground mobility domain are actually somewhat higher for the car-owning households than determined within this study.

5.3.2 Type formation limitations

Type formation provided the central analytical approach and preparatory method for the detailed mobility data evaluation of the KLIB households. The grouping of households along emissions and mobility-related household characteristics allowed for pattern recognition based on the characteristics' expressions or combinations. As shown in the research background (cf. section 2.2.4, *household living situation*) as well as during the discussion, in terms of socio-demographic characteristics, household income is one of the most important determinants of the household carbon footprint, especially in the mobility context. Accordingly, income was initially intended to serve as a characteristic in the distinction and formation of the household types. However, as already described in the type formation, this would have resulted in a wide dispersion of the sample into many, empirically underrepresented and thus inconclusive types (cf. section 3.2.3, *analysis of empirical regularity*). The sample was simply too

small to differentiate the types in more detail concerning income. Therefore, it was refrained from an income-related differentiation and instead relied on the average income determinations for the total sample by Reusswig, Lass and Bock (2020) as well as own referencing (cf. section 4.1, *equivalised disposable income*). On the basis of the types formed and the present results, additional regression analyses of income against emissions would nevertheless be conceivable and certainly of informative value. However, this would exceed the scope of this study. A differentiation of the types according to educational level or age would theoretically also be reasonable and probably insightful with regard to emissions and mobility. Yet, the correspondingly collected detailed data was lacking for this purpose.

As outlined in section 2.3.3, mobility behaviour is complex and influenced by a multitude of relevant factors – from the determinants of structural framework conditions to the affecting factors of individual preconditions for action (cf. Scheiner, 2016, pp. 684 ff.). Against the background of this complex constellation of influencing factors and the limitations of available data, it was not the objective of this study to describe the mobility behaviour of the households in detail. It is clear that this would only be meaningful to a limited extent. Instead, the objective was to provide robust statements on changes and differences in the mobility patterns of the household types in the context of emissions reduction based on mobility- and emissions-relevant household characteristics. In particular, focusing on the main drivers of mobility emissions of private households, i.e. MPT and air travel. In this respect, the performed type formation was sufficient apart from the income limitation.

6 Conclusions and recommendations

The overall objective of this study was to find out to what extent different urban household types reduce their household carbon footprint through voluntary action and changes in mobility behaviour within the real-world lab experiment KLIB. This included to enhance the understanding in which mobility domains behavioural changes for emissions reductions by voluntary efforts can be expected and where voluntariness reaches its limits. In synthesis of the results and with respect to the research questions, there are distinctly different, even contradictory changes in the mobility behaviour observable within ground mobility and air travel concerning the intended emissions reductions – depending on the initial conditions (household living situation, car ownership) of the household types, to a clearly varying extent.

In the scope of ground mobility, the present study has provided differentiated insights into how general environmental awareness combined with targeted interventions (carbon tracking, footprint information and feedback, social comparison and normative referencing) affect voluntary behavioural changes within everyday mobility of different household types. The RwL experiment KLIB constituted a *key event* for a changed behavioural context. It created an ‘opportunity window’ for behavioural change that could be leveraged by the households’ environmentally motivated intention for action, supported and promoted by the KLIB interventions, to disrupt (carbon-intensive) everyday mobility routines and behavioural *carbon lock-ins* and to establish new lower-carbon mobility forms and routines. Thus, on the one hand, it revealed that ambitious voluntary behavioural changes in everyday mobility are feasible at least within the special KLIB setting of the RwL. It was found that the different household types reduce emissions to varying extents depending on the *household living situation*, but particularly with regard to *car equipment*: In the case of the car-owning household types, the reduction of car use (transport performance) as well as a corresponding *modal shift* towards low-carbon modes of transport led to substantial absolute emissions reductions. Nevertheless, due to the absence of the carbon lock-in effects of car ownership, the car-free household types consistently exhibited lower

emissions balances compared to their counterpart types, and in some cases still achieved relatively considerable reductions. Therefore, on the other hand, the study also provided further evidence that behavioural and technological carbon lock-ins related to car ownership are distinct barriers to emissions reduction through (voluntary) behavioural change.

The particular relevance of projects like KLIB is also to demonstrate what is feasible and possible for individuals to reduce their carbon footprint and not at least to communicate this to the public. Carbon tracking combined with social comparison and normative referencing within a group can lead to the re-negotiation of existing, unsustainable social norms and in the process bring about the emergence of new, more sustainable norms of practice (De Dominicis *et al.*, 2019; Bamberg, Rollin and Schulte, 2020; Gössling, Humpe and Bausch, 2020; Ruhrort and Allert, 2021). Through appropriate media communication and coverage, as in the KLIB case (cf. Reusswig, Lass and Bock, 2020), spillover effects into the public sphere are conceivable. In this connection, Reusswig, Lass and Bock (2020) found that the carbon tracking indeed affected the 'carbon consciousness' of the participating households. Furthermore, it also stimulated social engagement (Reusswig, Lass and Bock, 2020). Behavioural economist Sean Ellis (2021) sees great potential for social comparison and normative referencing as drivers of behavioural change for climate protection. Speaking of a 'herd effect', he highlights the spillover effects of foregoing individuals or groups who lead change by good example, creating a positive vision of sustainable change that encourages others to emulate. This creates a social norm of sustainable behaviour change, which is among the most cost-effective measures to motivate individuals to adopt climate protection action (Ellis, 2021). Scientists from other disciplines likewise assess the creation and shaping of sustainable social norms as effective for far-reaching behavioural change in society if the framework conditions are appropriately provided (cf. Creutzig *et al.*, 2016; Nyborg *et al.*, 2016; Javaid, Creutzig and Bamberg, 2020). Javaid, Creutzig and Bamberg (2020) find the modal shift to low-carbon alternatives can be supported and enhanced by social influence in the form of collective social norms of low-carbon mobility. Ruhrort and Allert (2021), highlight the role of social norms

in mobility transitions as a key concept bridging individual behavioural change and the transformation of social structures. In this context, they argue that individuals can influence social norms, especially within ‘opportunity windows’, by both changing their own travel behaviour and participating in the public discourse on re-negotiating social norms. Individuals could perceive themselves as ‘carriers’ of social norms for low-carbon mobility and practices, which they actively perpetuate and promote by advocating them in their own social context and in public, thereby contributing to societal change (Ruhrt and Allert, 2021). This is exactly what the KLIB project encouraged and supported the participating households to do: they changed their everyday mobility behaviour (e.g. modal shift) and talked about it, critically discussed related social norms and practices, also concerning air travel (e.g. within live meetings and forum discussions), and increased their social engagement (e.g. by participating in political demonstrations) (cf. Reusswig, Lass and Bock, 2020). Last but not least, the KLIB project reinforced these processes through its media presence, the demonstration of KLIB case examples as well as the public dissemination and discussion of the findings (cf. Berliner Zeitung, 2019; Deutschlandfunk and Bock, 2019; Deutschlandfunk and Reusswig, 2019; PIK, 2019; Süddeutsche Zeitung, 2019; taz, 2019; Reusswig, Lass and Bock, 2020).

However, in relation to the research questions, this study (and the overall KLIB results) also clearly revealed limits of voluntary behavioural change: while most of the household types managed to reduce emissions clearly within the context of everyday ground mobility, again most of them failed markedly within the holiday context and air travel. On the contrary, emissions from air travel increased considerably in some cases, offsetting emissions savings from everyday ground mobility and even over-compensate them in most of the cases. The discussion of these findings with relevant literature revealed the environmental *attitude-behaviour gap* in the context of holiday travel to be a challenging problem and a clear barrier for voluntary behavioural changes within mobility and transport (cf. Hares, Dickinson and Wilkes, 2010; Cohen, Higham and Reis, 2013; Hergesell and Dickinger, 2013; Hibbert *et al.*, 2013; Kroesen, 2013; Juvan and Dolnicar, 2014). Holidays represent a completely different

behavioural context in which (newly established, low-carbon mobility practices) everyday mobility routines no longer apply. It is charged with symbolic values and social imaginaries of casualness, relaxation and the loosening or complete abandonment of everyday social norms (Cohen, Higham and Reis, 2013). *Behavioural costs* (e.g. monetary, time, or comfort costs) of choosing low-carbon alternatives to travel like long-distance trains are experienced higher in the holiday context which counteract a modal shift (cf. Diekmann and Preisendörfer, 2003). In addition, there are indirect psychological *rebound effects* like the *moral-licensing-effect*, which may tempt even environmentally convinced individuals (like in KLIB) to nevertheless travel by air in the holiday context (cf. Sanatorius, 2012). Conceivably relevant in relation to the professional backgrounds (largely academics and executives) of the KLIB sample is also a form of cultural capital – the bridging of distances as an expression of intercultural exploration, experience and education, of a cosmopolitan lifestyle and higher socioeconomic status, which clearly promotes air travel (cf. Larsen and Guiver, 2013; Williams, 2013; Gössling *et al.*, 2017). The attitude-behaviour gap within holiday contexts is thus problematic from a carbon footprint perspective, since associated air travel emissions can offset and even overcompensate for the savings achieved through behavioural changes in everyday mobility (cf. *Figure 19*).

Ultimately, in the context of holidays and air travel, it is neither adequate nor purposeful to expect voluntary behavioural changes. The western-centric public is largely unwilling to voluntarily change their holiday air travel behaviour for the sake of climate and environmental protection (cf. Barr *et al.*, 2010; Hares, Dickinson and Wilkes, 2010; Cohen, Higham and Reis, 2013; Higham *et al.*, 2013; Kroesen, 2013). Currently, air travel receives little political attention, with only 1 % of policies targeting aviation (Dubois *et al.*, 2019). This is a cause for concern against the backdrop of a steadily growing tourism and air travel industry in the long term, apart from the slump during the SARS-CoV-2 pandemic (cf. section 2.1; ITF, 2017, 2021). Political steering instruments and regulatory frameworks are needed to reduce or at least curb air travel and associated emissions. Likewise, with regard to technological and behavioural carbon lock-ins (cf. Seto *et al.*, 2016; Ivanova *et al.*, 2018; cf. section 2.2.4)

and the MPT (cf. section 2.1.1) there is no trend change in sight according to current projections (cf. Agora Energiewende, 2021; ITF, 2021). It becomes evident that it is crucial to change the regulatory frameworks and establish political steering instruments that improve, promote and extent low-carbon alternatives and create clear incentives for private households to change their mobility behaviour towards less air travel and MPT.

*Carbon pricing*²⁵, such as an effective emissions trading system or carbon tax, is a key cost-efficient measure to effective climate politics and climate protection (Boyce, 2018; UNFCCC, 2021). Carbon pricing shifts the cost and responsibility for climate change damages from the public to the polluters of GHG emissions. It creates a price signal that reduces or regulates GHG emissions while incentivising a shift in investment and use of emissions-intensive technologies towards low-carbon or carbon neutral technologies (UNFCCC, 2021). Thus, it generates clear incentives for behavioural change towards low-carbon lifestyles as well as for infrastructural and technological change and innovation towards the decarbonisation of all sectors (Boyce, 2018; IGES, Aalto University and Ltd., 2019; Agora Verkehrswende and Agora Energiewende, 2019; Kalkuhl, Knopf and Edenhofer, 2021; UBA, 2021c). This applies in particular to the transport sector, since steering impulses through increased fossil fuel prices are directly experienced by the consumer. Financial incentives are created to reduce the transport performance of carbon-intensive modes of transport and shift to low-carbon alternatives (UBA, 2021c). At the same time, several studies show that a carbon price can lead to more social justice in climate protection if it is designed appropriately. Socially unbalanced distribution effects can be avoided through corresponding redistribution from the generated revenues (cf. Boyce, 2018; Agora Verkehrswende and Agora Energiewende, 2019; FÖS and FEST, 2021; Kalkuhl, Knopf

²⁵ *Carbon pricing* curbs GHG emissions by imposing a fee on the emission of CO₂-eq and/or providing an incentive to emit less. It captures the external costs of carbon emissions (i.e. the costs borne by the public due to the damage caused by emissions) and shifts these costs to their source or polluters. The resulting price signal leads to a change in consumption and investment patterns and is intended to align economic development with climate protection. Carbon pricing usually takes the form of a carbon tax or an emissions trading system (cap and trade) (Boyce, 2018; UNFCCC, 2021).

and Edenhofer, 2021). Explicitly, Kalkuhl, Knopf and Edenhofer (2021) demonstrate for Germany, that a reduction of the electricity price through the counter-financing of the EEG levy and especially a per-capita redistribution mechanism would have a positive effect on the lower incomes. They highlight that a per-capita refund benefits the lowest-income households the most and even leads on average to a net relief of costs for them (Kalkuhl, Knopf and Edenhofer, 2021). In addition to a systematic improvement of the situation of households with lower or average income, households with children would in general also be among the beneficiaries of a carbon price with a corresponding redistribution model. Conversely, an appropriate carbon price has the strongest effect on those who emit the most, thus especially on frequent flyers and high-income households with high energy and fuel consumption (Agora Verkehrswende and Agora Energiewende, 2019; Kalkuhl, Knopf and Edenhofer, 2021). In this overall context, the carbon price can only fully exert its steering or incentive effect if it approximately covers the rising 'external (environmental) costs' of CO₂-eq emissions and if attractive low-carbon mobility alternatives are available (FÖS and FEST, 2021; Kalkuhl, Knopf and Edenhofer, 2021; UBA, 2021c). Accordingly, there is also a need to promote, subsidise and invest in low-carbon infrastructures and transport services (e.g. public transport systems, bike route network, e-mobility charging infrastructure etc.) (FÖS and FEST, 2021; UBA, 2021c). In particular for inter-city transport, the expansion and development of high-speed railway infrastructure is crucial as an attractive, but most important fast alternative to air travel. For international long-distance travel, however, renewably produced synthetic aviation fuels are indispensable in the long term, as air travel remains the only time-efficient mobility alternative on the longest routes (ITF, 2021).

In the EU, the European Union Emissions Trading System (EU ETS) was established in 2005. However, except for intra-European air transport, the transport sector and the building sector have not been included so far (EC, 2021b). In January 2021, a national emissions trading system (nEHS) was introduced in Germany for the sectors heat and transport with a fixed price of 25 euro per t CO₂ (BMU, 2019, pp. 25 ff., 2020). However, in order to achieve the required rapid transformation of the transport sector, the

currently set price path will not be sufficient to unfold an appropriate steering effect (Öko-Institut, Fraunhofer ISI and IREES, 2020; Kalkuhl, Knopf and Edenhofer, 2021; UBA, 2021c). Several studies indicate that significantly higher prices of at least 200 – 250 euros per t CO₂ will be needed to reach the emissions mitigation target for 2030 of the transport sector (cf. Kalkuhl, Knopf and Edenhofer, 2021; Pietzcker, Osorio and Rodrigues, 2021; UBA, 2021c, 2021h).

At the same time, there are still policy measures and environmentally harmful subsidies that promote motorised transport and air travel, which in turn reduces the steering and incentive effect of the carbon price. A recent study commissioned by the UBA (Burger and Bretschneider, 2021) showed a strong need for action on environmentally harmful subsidies in Germany, especially with regard to the transport sector. In total, environmentally harmful subsidies amounted to 65.4 billion euros in 2018, with transport accounting for the largest share with 30.8 billion euros. Of particular relevance are the paraffin tax exemption and the VAT exemption for international flights in the domain of air travel. And in relation to the MPT, the energy tax concession for diesel, the distance allowance and the company car privilege (Burger and Bretschneider, 2021). Concretely, such subsidies diminish incentives for behavioural change that lead to or involve a reduction of MPT and air travel as well as shifting to more efficient, low-carbon or environment-friendly modes of transport. On the contrary, they cause an growth of total transport volume, hence carbon emissions and, as in the case of air travel, an increase of the most carbon-intensive mode of transport (Burger and Bretschneider, 2021). Moreover, environmentally harmful subsidies in the transport sector almost consistently have negative distributional effects on private households, i.e. they benefit high-income households much more than low-income households (Burger and Bretschneider, 2021). Ultimately, the billions in savings from a consequent removal of environmentally harmful subsidies in the transport sector could be invested in the development and expansion of low-carbon infrastructures and modes of transport, such as an attractive, affordable and fast public transport or an extensive and safe bike route network (Burger and Bretschneider, 2021).

Considering the current state of research together with the findings of this study, the following overarching conclusions (1 and 2) and key recommendations for action (3 and 4) are derived: (1) lifestyle and behavioural changes of private households in the mobility domain have a substantial emissions reduction potential for the personal carbon footprint and could aggregated significantly contribute to the decarbonisation of societies. However, behavioural changes can only fully unfold their reduction potential if existing infrastructures are transformed and low-carbon transport systems, infrastructures and technologies are expanded, further developed and improved, i.e. if attractive, affordable and fast low-carbon transport modes are available and good conditions for active travel are created. (2) In the context of everyday mobility, voluntary changes in mobility behaviour like the shift to low-carbon modes of transport can lead to considerable emissions reductions depending on the household's living situation and car equipment. Nevertheless, car ownership remains a strong carbon lock-in and barrier to emissions reductions. Shaping social norms of low-carbon mobility practices by pioneering individuals and groups could induce far-reaching changes in social structures if the framework conditions are met. However, voluntary behavioural changes are context-specific and constrained by different counteractive effects and obstacles, particularly in connection with holidays and emissions-intensive air travel. This is problematic since air travel can offset or even overcompensate emissions savings from other areas. (3) Therefore, effective carbon pricing is crucial to create strong incentives for changing mobility behaviour and shifting towards low-carbon transport modes where possible. Consequently, this study recommends, in accordance with the scientific community and the Federal Environment Agency (cf. Agora Verkehrswende and Agora Energiewende, 2019; Kalkuhl, Knopf and Edenhofer, 2021; UBA, 2021c, 2021h), a timely increase and adjustment of the introduced fixed carbon price in Germany (nEHS) to cover actual external costs, in order to achieve its full steering effect. At the same time, a socially sustainable design should be guaranteed by complementary measures such as a per-capita redistribution from the generated revenues to prevent socially unbalanced distribution effects. (4) In addition, environmentally harmful subsidies (cf. Burger and Bretschneider, 2021) that conflict

with carbon pricing should consistently be removed in order to counteract technological and behavioural carbon lock-ins. Specifically, for air travel, the paraffin tax exemption and the VAT exemption for international flights should be abolished, and with regard to the MPT, the energy tax concession for diesel, the distance allowance and the company car privilege. The savings could be invested in the development and expansion of low-carbon infrastructures and modes of transport (e.g. high-speed railway network).

In this way, the incentives for frequent air travel and car driving are diminished while simultaneously the preconditions for changing mobility behaviour and shifting to low-carbon modes of transport are improved in a socially just and responsible manner.

7 Bibliography

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8 Appendix

A Data corrections by imputation

Table 3: Overview of corrected input errors²⁶

Household ID (user_id)	kw	Emissions: original	Emissions: analysis correction	Transport mode correction (error type)	kw trip ID	Imputation difference
28	14	73.08	57.96	oepnv → long_distance (select. error)	6	-15.12
28	15	42	27.6	oepnv → long_distance (select. error)	5	-14.4
28	24	168.7	111.1	oepnv → long_distance (select. error)	6	-57.6
28	26	43.4	29	oepnv → long_distance (select. error)	6	-14.4
34	18	43.4	4.4	oepnv → long_distance_green (select. error)	3	-39
44	12	205.94	29.14	oepnv → long_distance_green (select. error)	6	-176.8
44	17	98.63	22.38	oepnv → long_distance_green (select. error)	1	-76.25
44	20	58.8	12	oepnv → long_distance_green (select. error)	4	-46.8
44	30	214.76	9.76	oepnv → long_distance_green (select. error)	1	-204.98
44	31	40.11	16.51	oepnv → long_distance_green (select. error)	1	-23.6
44	32	193.97	13.86	oepnv → long_distance_green (select. error)	1	-180.11
44	33	201.6	14.4	oepnv → long_distance_green (select. error)	1	-187.2
44	46	117.6	16.94	oepnv → long_distance_green (select. error)	4	-100.66
54	13	93.57	15.57	oepnv → long_distance_green (select. error)	3	-78
54	30	32.22	7	Fahrzeug_1 (input error)	2	-25.22
54	31	30.12	4.9	Fahrzeug_1 (input error)	2	-25.22
54	47	137.9	20.9	oepnv → long_distance_green (select. error)	3, 4	-117
54	48	74.9	16.4	oepnv → long_distance_green (select. error)	4	-58.5

²⁶ For comparison and reference please find in the attached folder 'data analysis materials' the data analysis calculation spreadsheets 'MASTERFILE_mobilität' and 'Analysis_Hh-types_mobility'.

58	30	31.5	8.75	oepnv → long_distance_green (select. error)	3	-22.75
58	40	56	10.5	oepnv → long_distance_green (select. error)	4	-45.5
65	15	19.12	7.78	carsharing (calc. error)	1	-11.34
65	16	61.27	7.78	carsharing (calc. error)	1	-53.49
85	8	207.71	93.31	oepnv → long_distance_green (select. error)	6	-114.4
85	13	95.4	37.13	oepnv → long_distance_green (select. error)	5	-58.27
85	16	156.45	26.45	oepnv → long_distance_green (select. error)	6	-130
92	8	98.84	17.59	oepnv → long_distance_green (select. error)	1	-81.25
92	24	79.1	7.6	oepnv → long_distance_green (select. error)	1	-70.5
92	32	168	12	oepnv → long_distance_green (select. error)	4	-156
92	39	44	8.25	oepnv → long_distance_green (select. error)	3	-35.75
92	41	66.15	7.65	oepnv → long_distance_green (select. error)	5	-58.5
110	1	108.45	50.7	oepnv → long_distance_green (select. error)	2	-57.57
110	8	114.6	112.44	oepnv → short_distance (select. error)	7	-2.16
110	9	118.89	94.89	oepnv → long_distance (select. error)	7	-24
110	10	95.2	71.2	oepnv → long_distance (select. error)	7	-24
153	35	77	50.6	oepnv → long_distance (select. error)	1	-26.4
153	48	45.64	31.96	oepnv → long_distance (select. error)	1	-13.68

B Boxplots – dispersion and location parameters of the main variables

Boxplots of baseline and KLIB emissions from ground mobility by household type

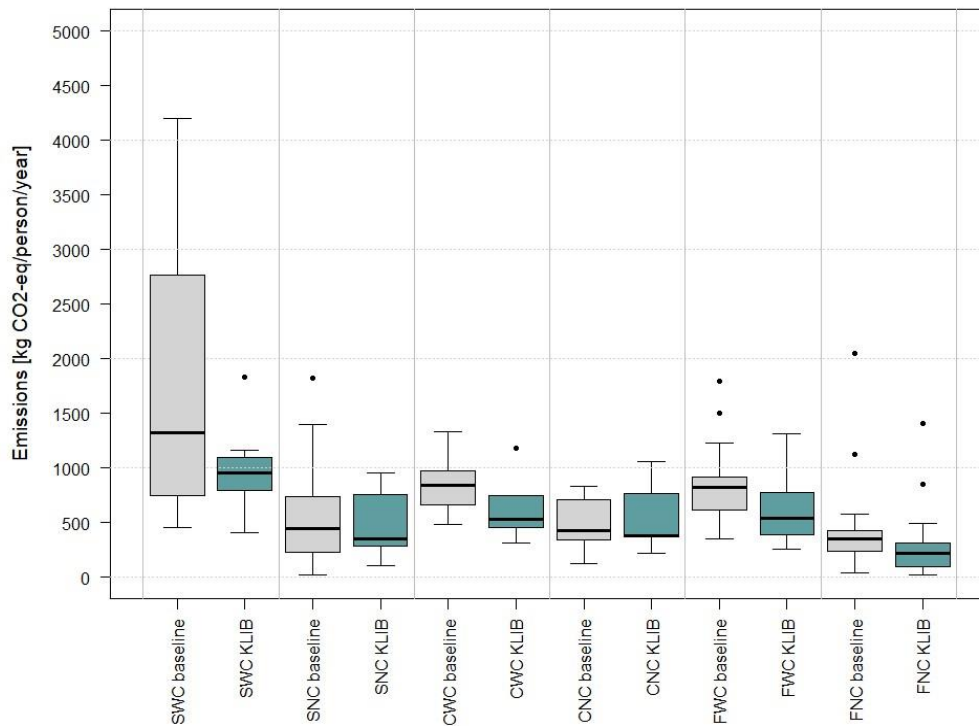


Figure 22: Boxplots of baseline and KLIB emission variables of ground mobility [kg CO₂-eq/person/year]: showing dispersion and location parameters of individual cases (households) per household type.

Boxplots of emission differences in ground mobility by household type

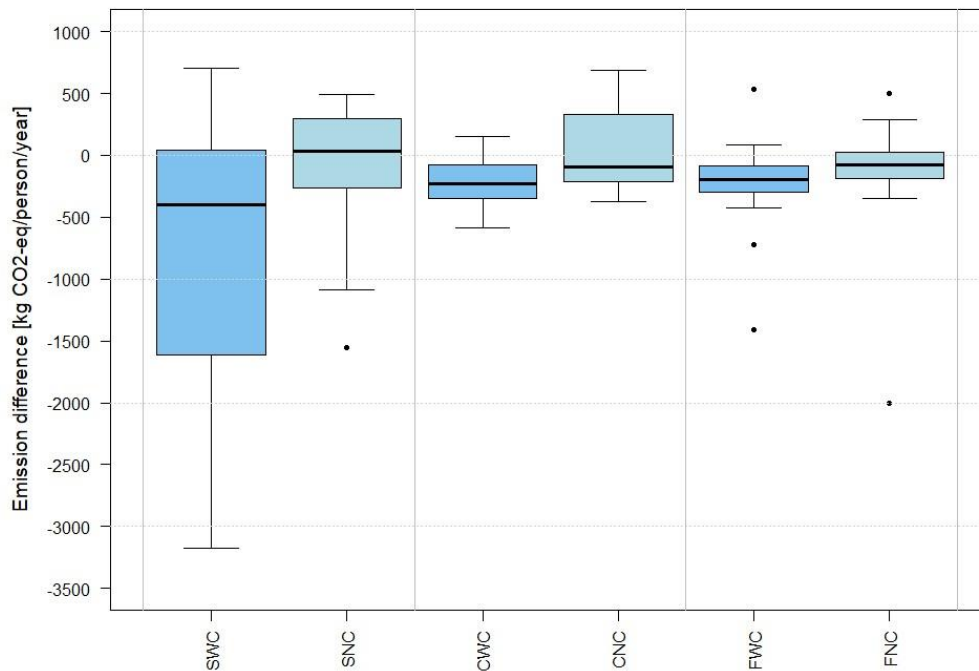


Figure 23: Boxplots of emission difference variables (baseline/KLIB) of ground mobility [kg CO₂-eq/person/year]: showing dispersion and location parameters of individual cases (households) per household type.

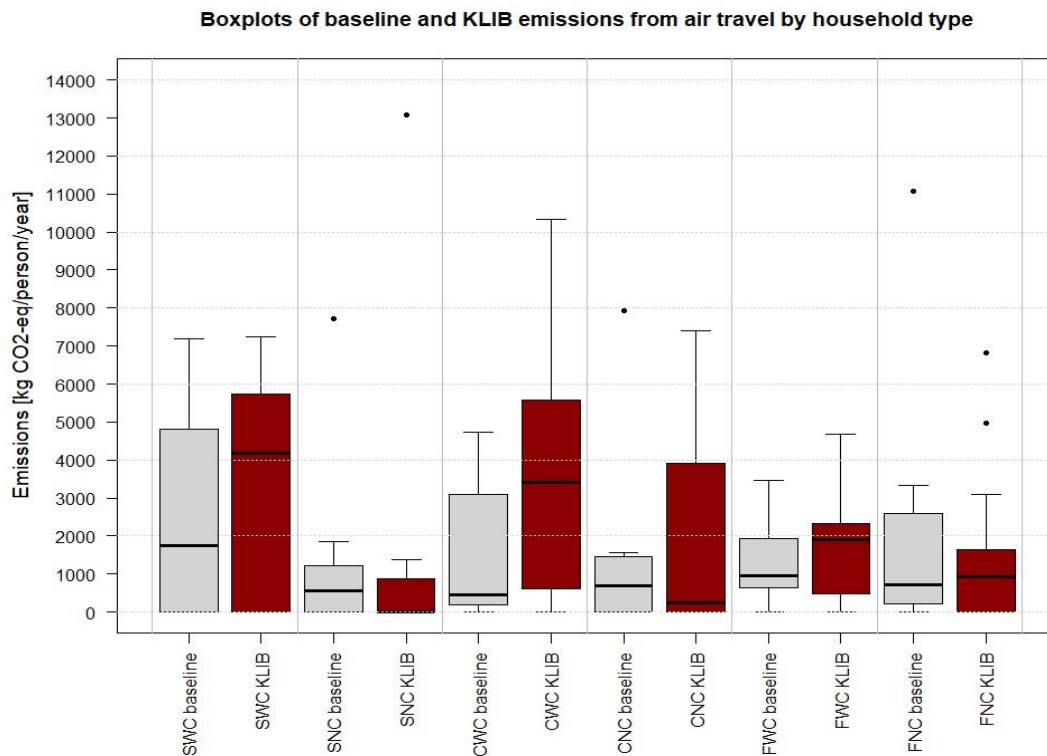


Figure 24: Boxplots of baseline and KLIB emission variables of air travel [kg CO₂-eq/person/year]: showing dispersion and location parameters of individual cases (households) per household type.

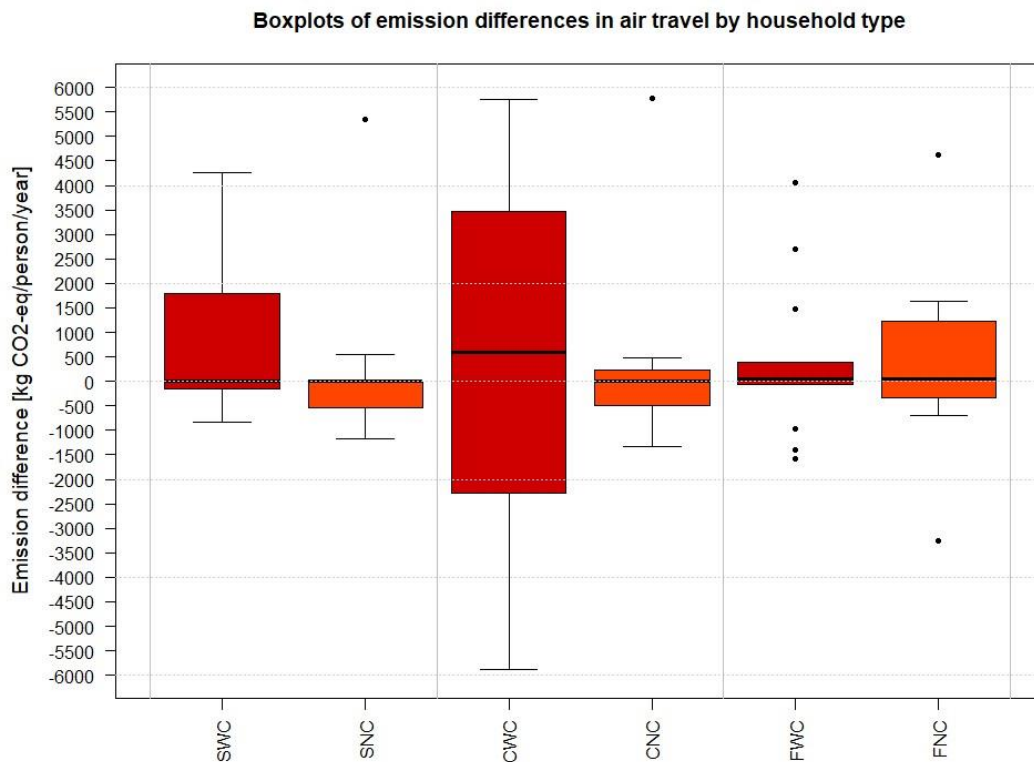


Figure 25: Boxplots of emission difference variables (baseline/KLIB) of air travel [kg CO₂-eq/person/year]: showing dispersion and location parameters of individual cases (households) per household type.

Boxplots of baseline and KLIB total transport performance by household type

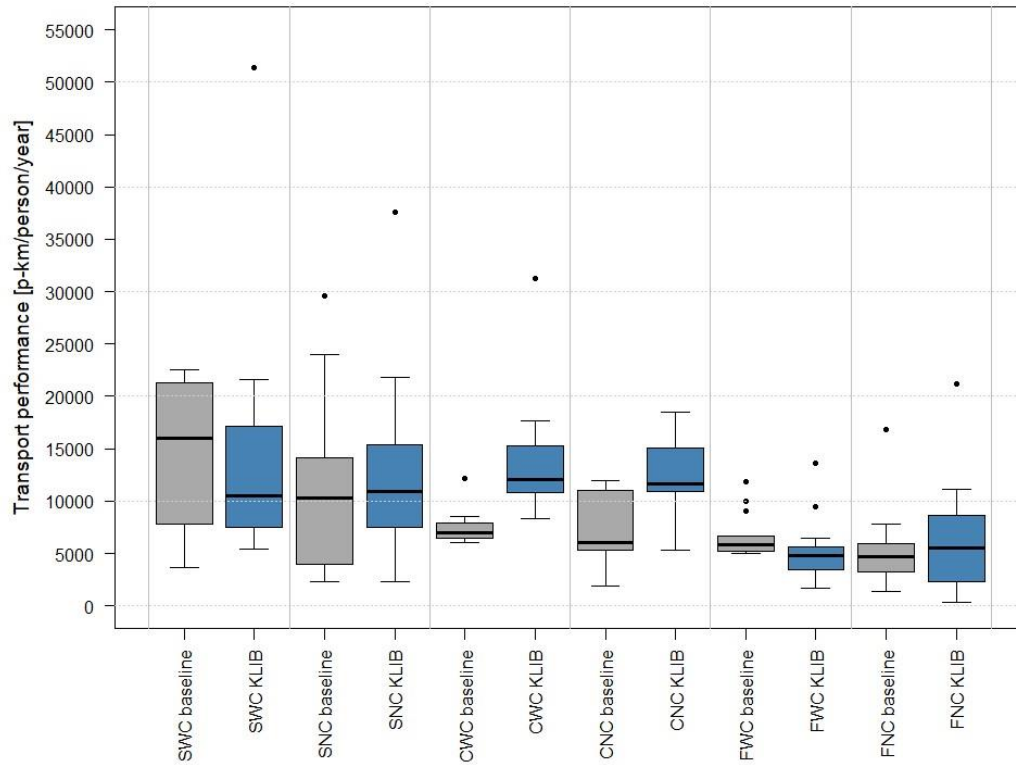


Figure 26: Boxplots of baseline and KLIB total transport performance variables [p-km/person/year]: showing dispersion and location parameters of individual cases (households) per household type.

Boxplots of total transport performance differences by household type

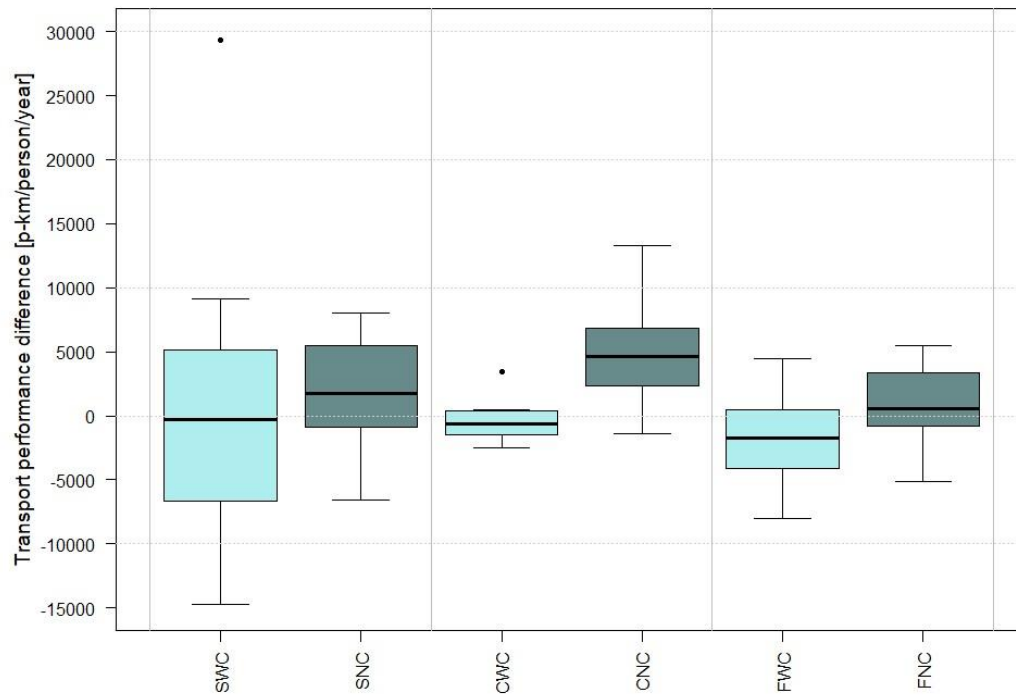


Figure 27: Boxplots of total transport performance difference variables (baseline/CLIB) [p-km/person/year]: showing dispersion and location parameters of individual cases (households) per household type.