Exploring the impact of shared mobility services on carbon and toxic emissions across all eHUBS cities and scaling-up for Manchester case study

Deliverable D.T2.7.1

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1. Introduction

The transport sector is a significant contributor to climate change because of its substantial emission of greenhouse gases (GHG). In 2020, 16.2% of the total emissions globally came from the transport sector, of which 73.5% was from road transport (Hannah, 2020). To avoid further escalation of climate change, countries and cities have pursued policies and strategies for decarbonisation of transportation, especially for road transport (Laakso, 2017). Shared mobility services including shared-bike, shared-car and ridesharing, are being promoted as one of the possible strategies offering several potential benefits, such as reductions in car ownership (and corresponding embedded carbon) and individuals' annual vehicle kilometres travelled (VKT) by promoting mode shift to other more sustainable modes of transport (including walking, cycling and public transport). eHUBS offer in one place users access to at least two of a range of shared electric vehicles, such as e-scooters, e-bikes, e-cargobikes and e-cars and have been demonstrated to be attractive to specific cohorts of the population depending on their demographics and mobility choice (Bösehans *et al.*, 2021). Mobility services have been shown to reduce transport emissions (Machado *et al.*, 2018; Arbeláez Vélez and Plepys, 2021) but previous research has not quantified the emissions of actual trip making which has been demonstrated to have potential to shift to shared mobility when shared mobility options are available. This deliverable investigates the research question "Do eHUBs services contribute to reducing transport impact on the environment?" Section 2 describes the case study, Section 3 the methodological approach for the estimations of GHG and air quality emissions, Section 4 articulates the results and discussion and finally in section 5 conclusions are drawn.

2. Case Study

The first questionnaire (QS1), administered between March and December 2020, targeted at non-users of shared mobility, was created to introduce the concept of eHUBs to the general population and to measure respondents' attitudes, demographics, general travel behaviour and traveller identity, as well as current use of shared vehicles. Respondents also were asked to indicate their intention to use eHUBs in the future and to identify any perceived barriers related to the uptake of eHUBs.

The second questionnaire (QS2), administered between September 2021 and January 2022, was targeted at both users and non-users of shared mobility. As in the first questionnaire, non-users were asked about their intention to use shared electric vehicles from eHUBS in the future, in addition to their intention to use different types of shared electric vehicle for different trip purposes. Shared mobility users, defined as using shared vehicles at least once per month, were asked about the nature of their shared mobility trips (e.g., modes used, frequency, typical trip distance, and trip purpose), mode substitution patterns (based on their last recalled shared mobility trip), as well as their attitudes towards and experience with shared (electric) vehicles and shared mobility providers.

3. Methodological Approaches

3.1 Overview

Figure 1 illustrates the framework for the estimation of GHG emissions which is referred to as equivalent carbon emissions as this also takes into account other main GHGs in the Earth's atmosphere which are water vapour, methane (CH_4), Nitrous Oxide (N_2O) and Ozone (O_3). There are two main steps. The first creates the tailpipe emissions factors and the second uses the data from actual trips made by car defined in the questionnaires along with the emissions factors to estimate emissions for (a) the maximum possible if all trips shifted to shared mobility (b) the potential shift if eHUBS were available to all early majority and (c) actual trips reported by the users of eHUBS. Given the eHUBS aimed to substitute single/round trip journeys the eHUBS questionnaire by Bösehans *et al.* (2022) revealed that 75% of eHUBS users travelled typically up to distances of about 6 mile/10km, therefore the analysis of the emissions presented in this deliverable is confined to these reported short distance trips.

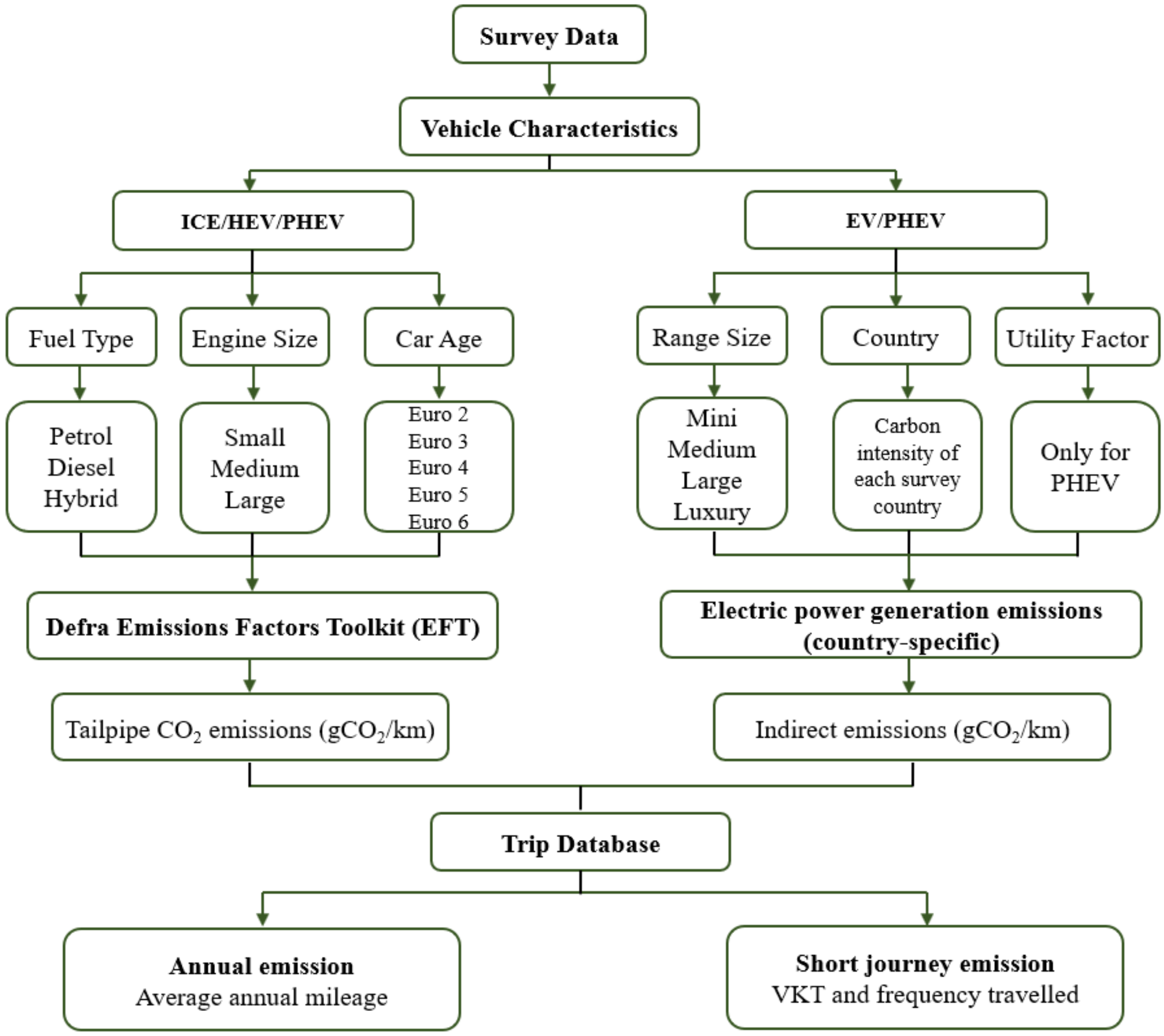


Figure 1. Framework for the estimation of GHGs emission

Electric vehicles (EVs) have onboard batteries that are charged with grid electricity, and have zero tailpipe emissions at point of use. However, indirect carbon emissions generated by power plants need to be considered. Therefore, the first step was to take into account the emission rates of the different mix of methods of electricity generation (including coal, wood pellets, nuclear, water, wind, solar) employed in the European Countries. In the current study, for the Battery EVs (BEVs), including hybrid EVs (HEVs), whether petrol HEVs or diesel HEVs or plug-in petrol EVs (PHEVs), the indirect emissions were considered also. This was achieved by using BEV electricity efficiency multipliers that are specific to the electricity generation of each country (Märtz *et al.*, 2021). The source of electricity generation and carbon intensity of each eHUBS country is shown in Table 1. For the PHEVs, the indirect emissions are calculated using BEV electricity efficiency multiplied by the specific emissions from the electricity generation and a utility factor.

The second step was mapping the questionnaire data to calculate the direct tailpipe emissions for conventional petrol and diesel vehicles, and hybrid vehicles, using the Defra emission factor toolkit (EFT). The Defra emission factor is based on the COPERT 4 consistent with the European directive on national emission limits (Boulter *et al.*, 2009). Three variables including fuel type, engine size and car age collected in the eHUBS questionnaire QS1 and QS2 were used in the data mapping process.

Individuals' car-related annual emission was calculated as follows:

$$Annual\ emission = Emission\ fator\ x\ Average\ annual\ mileage \qquad (1)$$

Where: the emission factor depends on the participants' specific vehicle and fuel type and age; average annual mileage using the data obtained from QS1 and QS2

Given the respondents of the questionnaire reported the number of car trips less than 6 miles (10km), individuals' reported car-related short journey emission was calculated as follows:

$$Short\ journey\ emision = Emission\ factor\ x\ VKT\ x\ trips\ frequency \qquad (2)$$

Where: emission factor depends on the participants' specific vehicle and fuel type and age; VKT and trips frequency data obtained from QS1 and QS2.

Table 1. Carbon intensity of electricity generation mixes in Germany, United Kingdom, Netherlands, France and Belgium in 2020 (Hannah *et al.*, 2020).

	Electricity generation mix, %								**Carbon intensity, gCO_2eq/kWh**
Country	Coal	Gas	Hydropower	Solar	Wind	Oil	Nuclear	Other Renewables	
Germany	23.7	16.2	3.3	9.0	23.7	4.0	11.3	8.9	301
United Kingdom	1.7	36.6	2.2	4.4	24.2	2.5	17.0	11.6	209
Netherlands	7.2	59.8	0.1	6.4	12.5	4.5	3.3	6.3	318
France	0.8	6.5	11.7	2.5	7.4	2.2	67.2	1.7	55
Belgium	0.1	30.3	0.3	5.4	14.4	4.1	39.3	6.0	192

3.2 Emissions Estimation for Different Scenarios

Figure 2 illustrates the scenarios in the calculation of the emission impacts. For survey QS1, reported journey emissions were estimated for 2493 participants who were not eHUBs users. This provides the maximum emissions savings if all short journeys were shifted to shared mobility. Therefore, for the first experiment, we have investigated the effect of their intension to use shared mobility services on car-related short-journey/annual emission between different eHUBS cities. For survey QS2, of 980 participants, 247 were identified as shared mobility users and 733 non-users. For the second experiment, the effects on car-related short-journey/annual emission of actual users adopting shared mobility services were estimated. Emissions for these two scenarios were estimated for the different eHUBs cities. A final step of the analysis was to estimate the actual reductions of emissions achieved by the 247 users shifted to eHUBs and presented in the next section. Detailed calculation was discussed in **Section 3.2.1**.

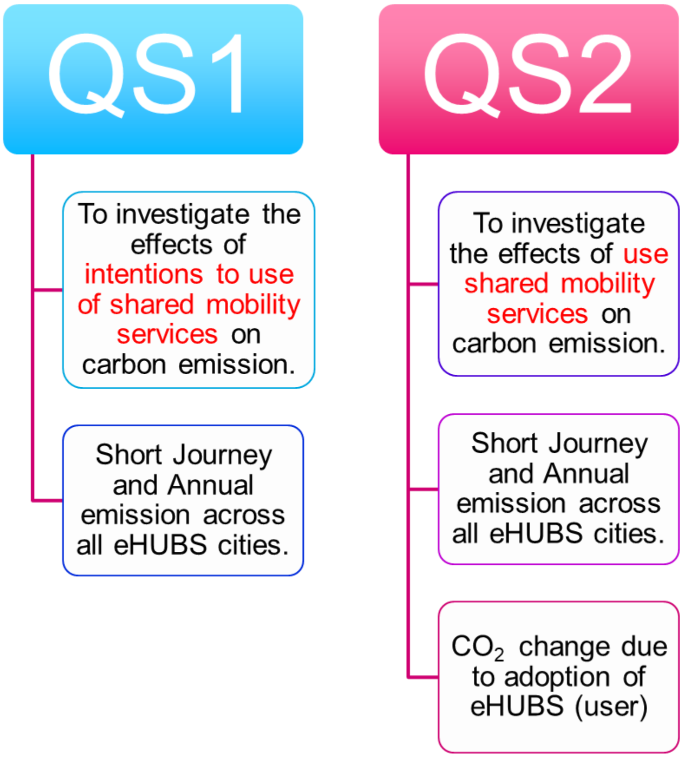


Figure 2. Flow diagram of CO_2 scenario estimates

3.2.1 Individual emission saving

Passenger cars generated higher carbon emissions of GHGs per person per VKT compared to other road transport modes, which accounts for 44% of total road-transport emissions (Arbeláez Vélez and Plepys, 2021). Moreover, based on previous research carried out by Bösehans *et al.*

(2021), the largest group of potential eHUBS users (early adopters and early majority) are mostly car users, thus potentially offering the greatest emissions reduction. Therefore, in this analysis, the car-related emission reduction due to the adoption of eHUBs was investigated.

Emissions saving per passenger-kilometre for car trips modes were calculated as follows:

$$Emission\ Saving = Pre_{car\ activity} \times E_{car} - [Aft_{car\ activity} \times E_{car} \times (1 - \%\ mode\ split) + eHUBs_{activity} \times E_{eHUBS} \times \%\ mode\ split] \quad (3)$$

Where: $Pre_{car\ activity}$ represents the car trips activity before using eHUBS, including trip distance and trip frequency; E_{car} is the emission factor of individual type of car; $Aft_{car\ activity}$ represents activity of car trips after adoption of eHUBS; $eHUBs_{activity}$ represents eHUBS trips activity including trip distance and frequency; E_{eHUBS} is the emission factor of shared vehicles including shared e-car, e-bike and e-cargobike; $\times\ \%mode\ split$ is the percentage of last trip substituted by shared e-vehicles.

Trip distance data and percentage of mode spilt were obtained from QS2 user survey, while trip frequency data was obtained based on previous studies. Detailed information is discussed in **Section 4.4**.

Apart from CO_2 emissions saving, the effect of the switch to the use of eHUBS on toxic emissions (NOx, $PM_{2.5}$ and PM_{10}) was estimated. The toxic emission saving was calculated according to equation 3, with emission factors of NOx, $PM_{2.5}$ and PM_{10} for the types of vehicles and shared e-vehicles reported by the users.

3.3 Scaling-up individual emission savings to geographic areas

In the original proposal the plan was to carry out the scaling-up of individual emission savings using the transportation model SATURN, Simulation, and Assignment of Traffic to Urban Road Networks. The SATURN model was investigated but the zone to zone distances exceeded those that were reported by the majority of users of eHUBS e-mobility. In other words, the SATURN model could provide no detail on the within zone trips which were synonymous with the shorter trips found most appropriate to the eHUBS users. A different approach was developed and described in this section. How emission savings was calculated for individuals who adopt eHUBS was explained in **Section 3.2**. In order to estimate potential savings across wider populations, be it a small zone within a city or an entire region, a scaling up exercise is required. The research carried out by Bösehans *et al.* (2021) identified a specific cluster of individuals, the car-dependent families, that are predicted to not only form the majority of eHUBS ‘early adopters’, but also present the greatest opportunity for emission reduction due to their current mode of transport. The scaling up methodology outlined in this report uses the proportion of households within a population that are car-owning with dependent children to determine the propensity to adopt eHUBS and therefore the emission saving potential of the area in which they reside.

Manchester, an eHUBS test city, resides in the North West region of England and was used as a case study to test this scaling up methodology by considering different geographical magnitudes. In the UK, the Office for National Statistics is the UK’s largest independent producer of official statistics, including data related to population, society and the labour market at national, regional and local levels. Therefore, it is the ideal dataset to determine the proportion of “car-dependent families”.

Two scenarios for potential emission savings have been applied to different locations at different geographic scales. Both scenarios consider 100% of the car-dependent families will switch to eHUBS for their main journey. This represents the impact of the best possible outcome. Further research will better inform this percentage, for example they could be determined by policy targets, similar to carbon savings scenarios in the Propensity to Cycle Tool (Lovelace *et. al.,* 2017).

Scenario 1 is the most optimistic of the two, and will assume widespread accessibility to eHUBS across the entire geographic area in consideration.

Scenario 2 demonstrates the potential effectiveness of a policy that only targets locations with the highest concentration of eHUBS early adopters. For this, a comparison has been made in Manchester of the areas with the most and the least of the early eHUBS-adopting, car-dependent families.

3.4 Statistical analysis

For QS1 analysis, the Kruskal-Wallis H test was used to determine if there are statistically significant differences in the annual/short-journey emissions between the vehicle types preferred by users of shared mobility services on annual/short-journey emissions. If the Kruskal–Wallis test is significant, the Dunn test will be performed as a post-hoc analysis to determine which groups differ from each other group.

For QS2 analysis, Wilcoxon signed-rank test was used to understand whether there was a statistically difference on annual/short-journey emissions between shared mobility users and non-users. Also, the Kruskal-Wallis H test was used to determine if there are statistically significant differences between different cities on users' emissions saving. Please note that all statistically tests were carried out at a 95% level of confidence.

4. Results and discussion

4.1 Emission factors for each type of vehicle

CO_2 Emission rates (g/km) for petrol and diesel vehicles are shown in **Figures 3 and 4**, respectively. CO_2 emissions for petrol car ranged from 104 to 292g/km, whilst for diesel car ranged from 77 to 240g/km. These results are consistent with lower CO_2 emissions for diesel compared to petrol vehicles.

Figure 5 shows the emission rates for full petrol hybrid and diesel hybrid vehicles. CO_2 emissions for full petrol hybrid car ranged from 70 to 181g/km, whilst for full diesel hybrid car ranged from 58 to 139g/km. Full hybrid vehicles with lower CO_2 emissions compared to conventional ICE vehicles.

Plug-in petrol hybrid vehicles have car age less than 9 years old; their emission rates are shown in **Figure 6**. The tailpipe emission of plug-in hybrid vehicles ranged from 33 to 64g/km, while their indirect emissions vary between different countries. Indirect emission of plug-in petrol hybrid cars in France is 6g/km, which is lower than for Belgium (20g/km), United Kingdom (21 g/km), Germany (31g/km) and Netherlands (33g/km). In France, the main fuel used to generate electricity is nuclear (67.2%), and this is the likely reason why plug-in petrol hybrid vehicles in France have lowest indirect emissions.

Similar results were found for electric cars' emissions rates (**Figure 7**). Electric car in France with lower CO_2 emissions ranged from 8 to 11g/km compared to Belgium (28-40g/km), United Kingdom (31-43g/km), Germany (44-62g/km) and Netherlands (46-66g/km).

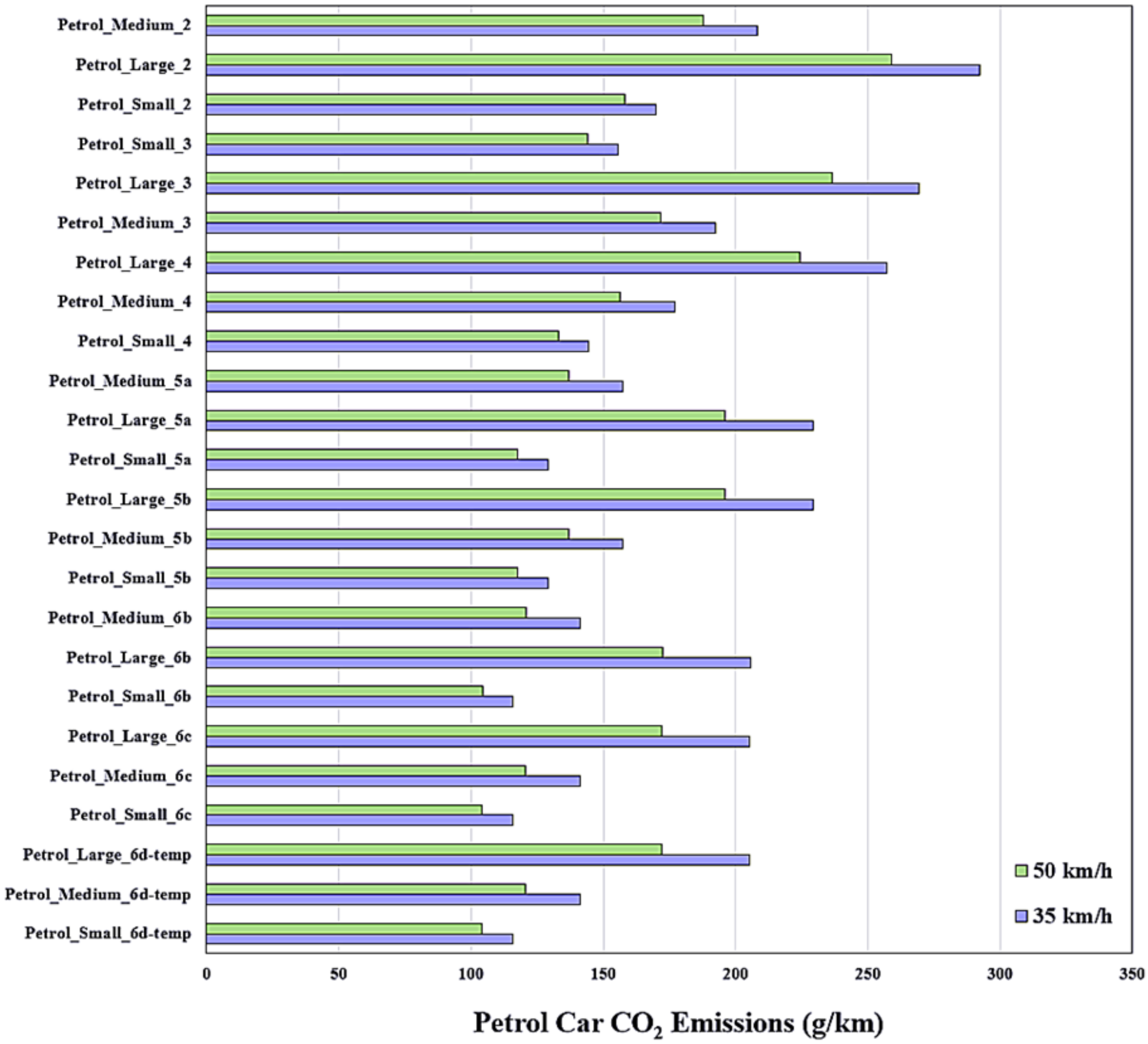


Figure 3. Petrol car CO_2 emission rates

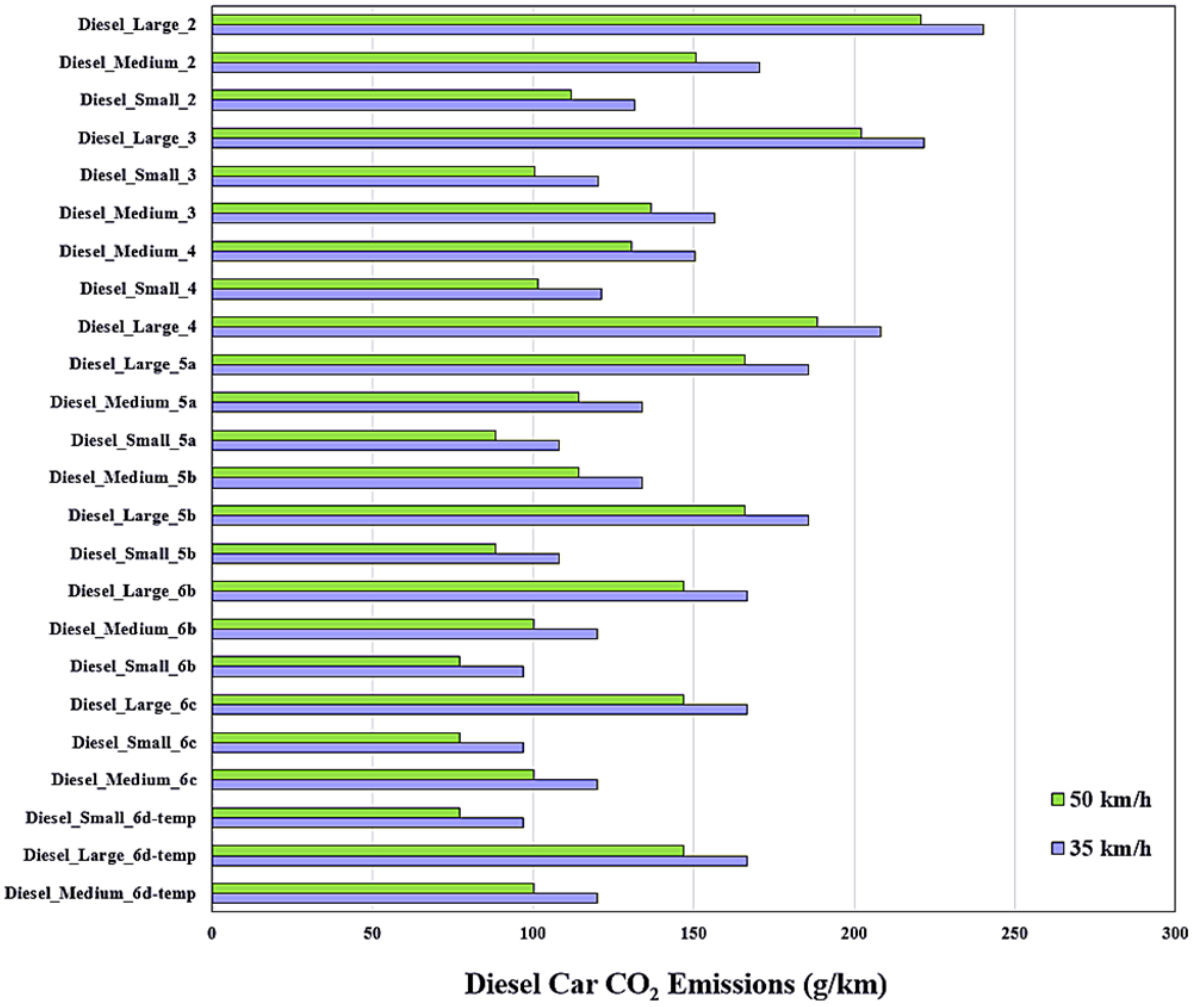


Figure 4. Diesel car CO_2 emission rates

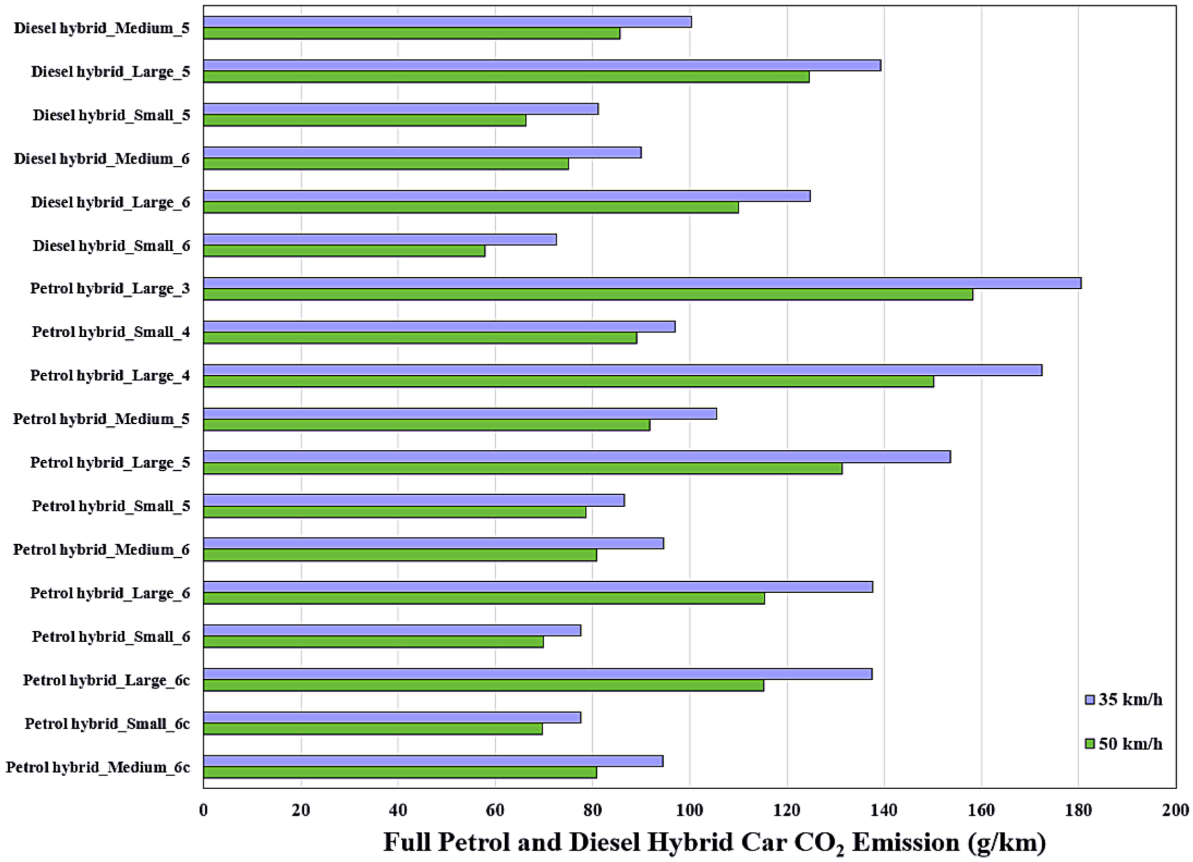


Figure 5. Full petrol and diesel hybrid car CO_2 emission rates

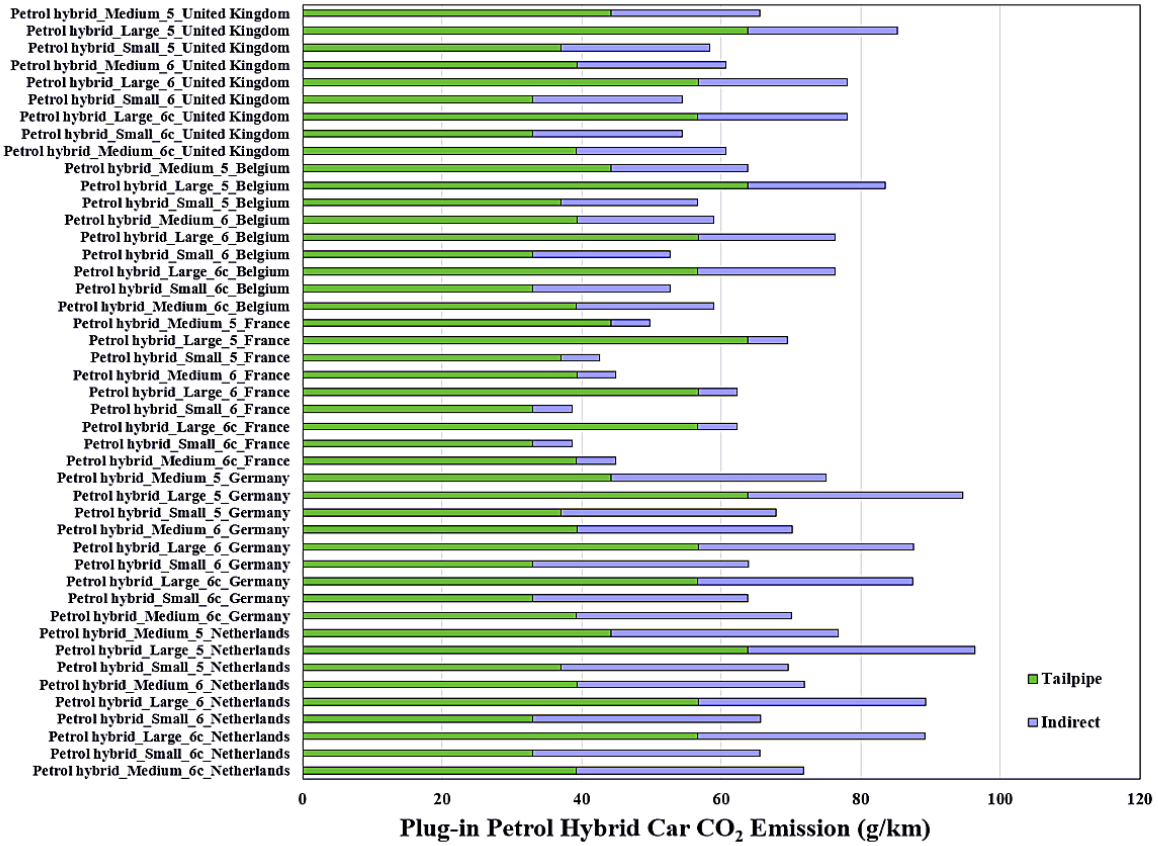


Figure 6. Plug-in petrol hybrid car CO_2 emission rates

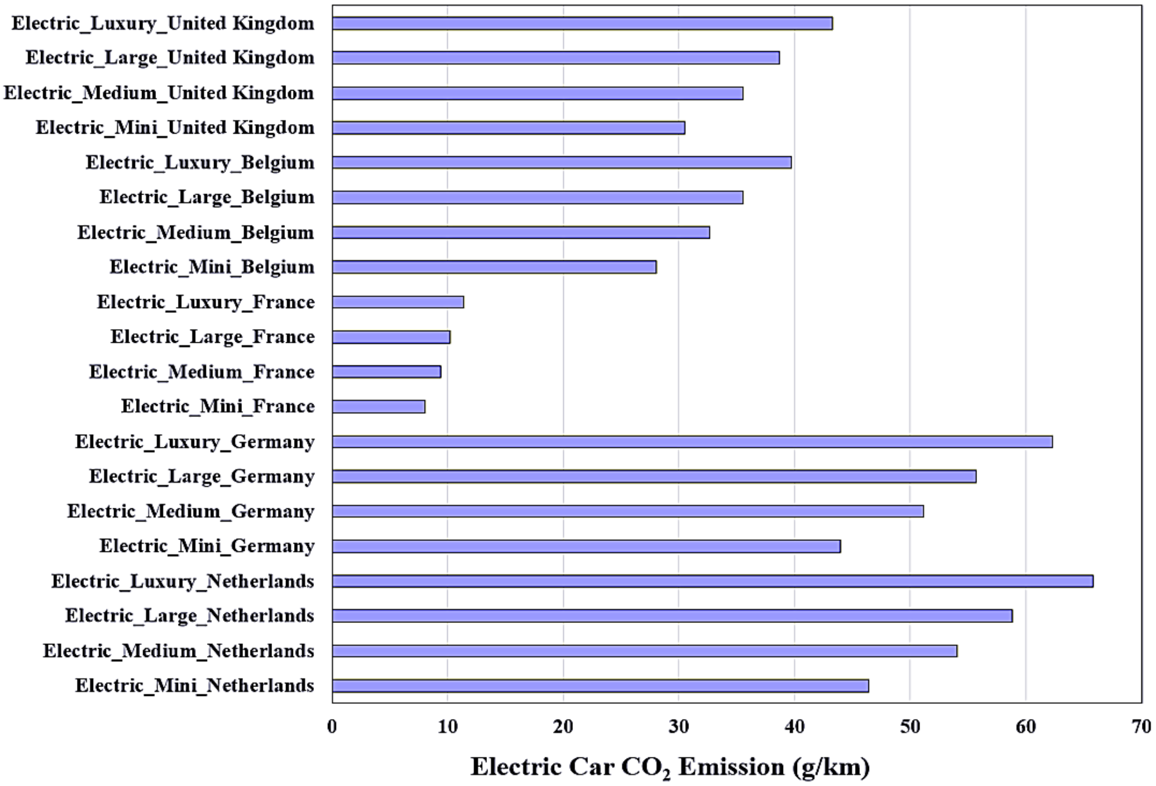


Figure 7. Electric car CO_2 emission rates

4.2 The effect of intension to use shared mobility services on short journey/annual emissions across all cities

The distribution of individual's short-journey emission for all eHUBS cities for QS1 survey is shown in **Figure 8**. Amsterdam received 345 responses, with mean and median values at 0.69 and 0.62kg/day, respectively. Arnhem received 20 responses, with mean value at 0.93kg/day and median value at 1.27 kg/day. Dreux obtained 184 responses, with mean and median values at 0.88 and 0.86kg/day, respectively. Kempten had 223 responses, with mean and median values at 0.69 and 0.64kg/day, respectively. Leuven achieved 153 responses, with mean value at 0.49kg/day and median value at 0.42kg/day. Manchester with 342 responses, with mean value at 0.69kg/day and median value at 0.68kg/day. Nijmegen had 59 responses, with mean value at 0.54kg/day and median value at 0.37kg/day. Clearly there are many factors coming into play when estimating carbon emissions but generally the further the distance you travel the more energy you use, therefore higher the emissions. However, one can argue that in those countries with lower carbon intensive energy generation theoretically can travel further by e-mobility than another country with higher carbon intensive energy generation to achieve the same emission. Given the response rate to the questionnaires varied so much from 20 to 345 there are limitations in comparing results across the seven cities.

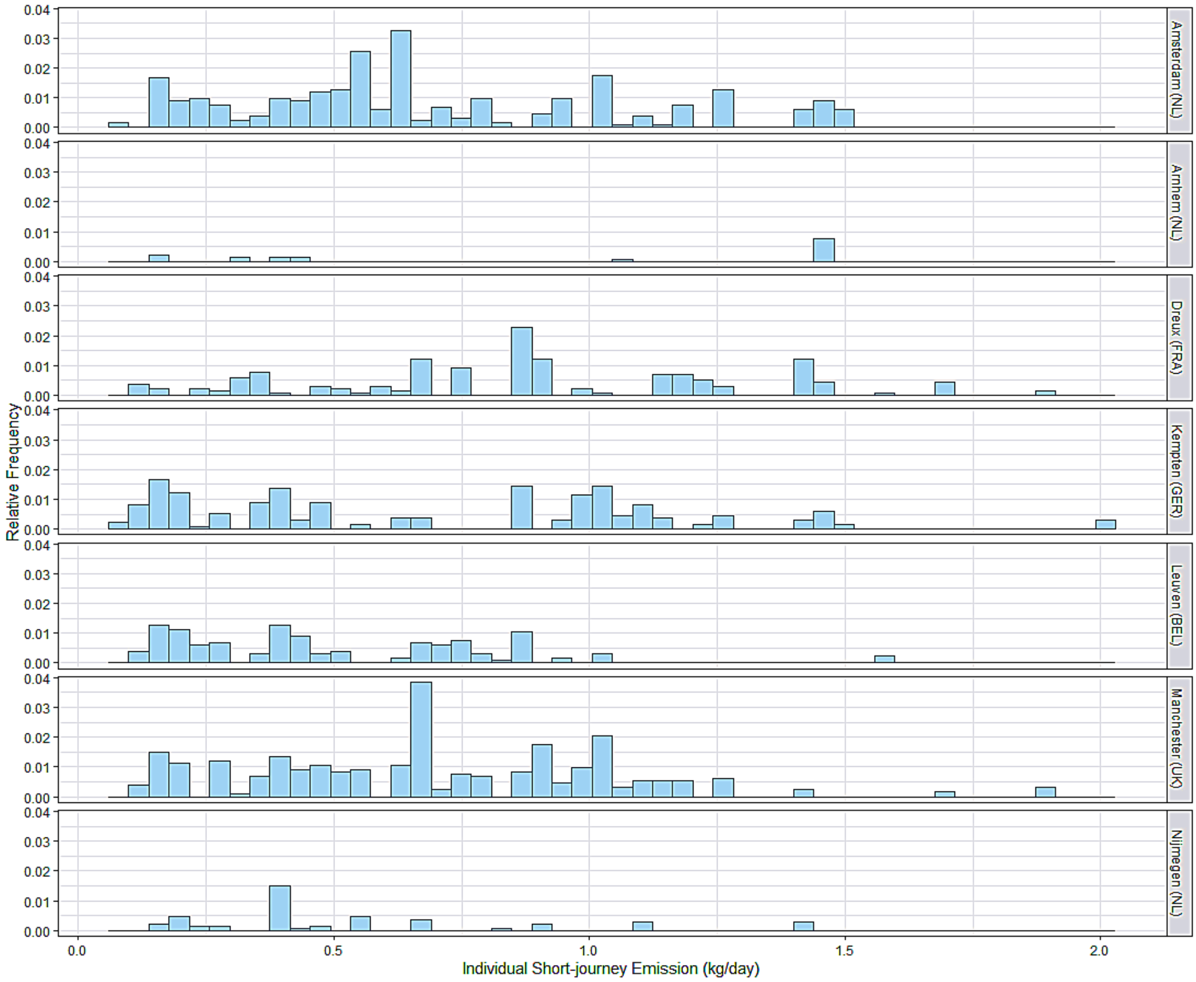


Figure 8. Distribution of individual's short-journey emissions (kg/day) of all cities for QS1 survey

Figure 9. Average short-journey emissions (kg/day) of all cities for QS1 survey

Average short-journey emissions (kg/day) for the cohort of survey respondents across all cities for QS1 survey are shown in **Figure 9**. Comparing the short-journey emissions estimates for users with intension to use shared mobility across all eHUBS countries, a statistically significant difference was found between the different shared modes for Amsterdam ($\chi^2(3)=39.01$, $p < 0.001$), Arnhem ($\chi^2(3)=17.15$, $p < 0.001$), Dreux ($\chi^2(3)=11.14$, $p=0.01$), Kempton ($\chi^2(3)=15.40$, $p < 0.001$) and Manchester ($\chi^2(3)=22.30$, $p < 0.001$). Specifically, for Amsterdam, with a mean short journey emission of 0.84kg/day use of shared bike, 0.83kg/day use of shared e-scooters, 0.69kg/day use of shared car and 0.58kg/day for participants who are not interested to use any shared vehicles. The post hoc Dunn test showed that short journey emission of no shared interest participants was statistically significantly lower to shared bike ($p=0.01$), shared e-scooters ($p<0.001$) and shared car ($p=0.007$). For Arnhem, with a mean short journey emission of 1.48kg/day for intension to use shared bike, 1.48kg/day for intension to use shared e-scooters, 1.05kg/day for intension to use shared car and 0.30kg/day for participants who are not interested to use any shared vehicles. The post hoc Dunn test showed that short journey emission of no shared interest participants was statistically significantly lower to shared bike (p=0.004) and shared e-scooters (p=0.002). For Dreux, with a mean short journey emission of 0.91kg/day for intension to use shared bike, 0.44kg/day for intension to use shared e-scooters, 0.5 kg/day for intension to use shared car and 0.91kg/day for those participants who are not interested to use any shared vehicles. The post hoc Dunn test showed that short journey emission of no shared interest participants was statically significantly higher to shared e-scooters (p=0.02). For Kempten, with a mean short journey emission of 1.04kg/day for use of shared bike, 0.73kg/day for use of shared car and 0.65kg/day for participants who are not interested to use any shared vehicles. The post hoc Dunn test showed that short journey emission of no shared interest participants was statistically significantly lower to shared bike ($p < 0.001$). For Manchester, with a mean short journey emission of 0.87kg/day for intension to use shared bike, 0.53kg/day for shared e-scooters, 0.95kg/day for shared car and 0.67kg/day for participants who are not interested to use any shared vehicles. The post hoc Dunn test showed that short journey emission of no shared interest participants was statistically significantly lower to shared bike (p=0.005) and shared car (p=0.005).

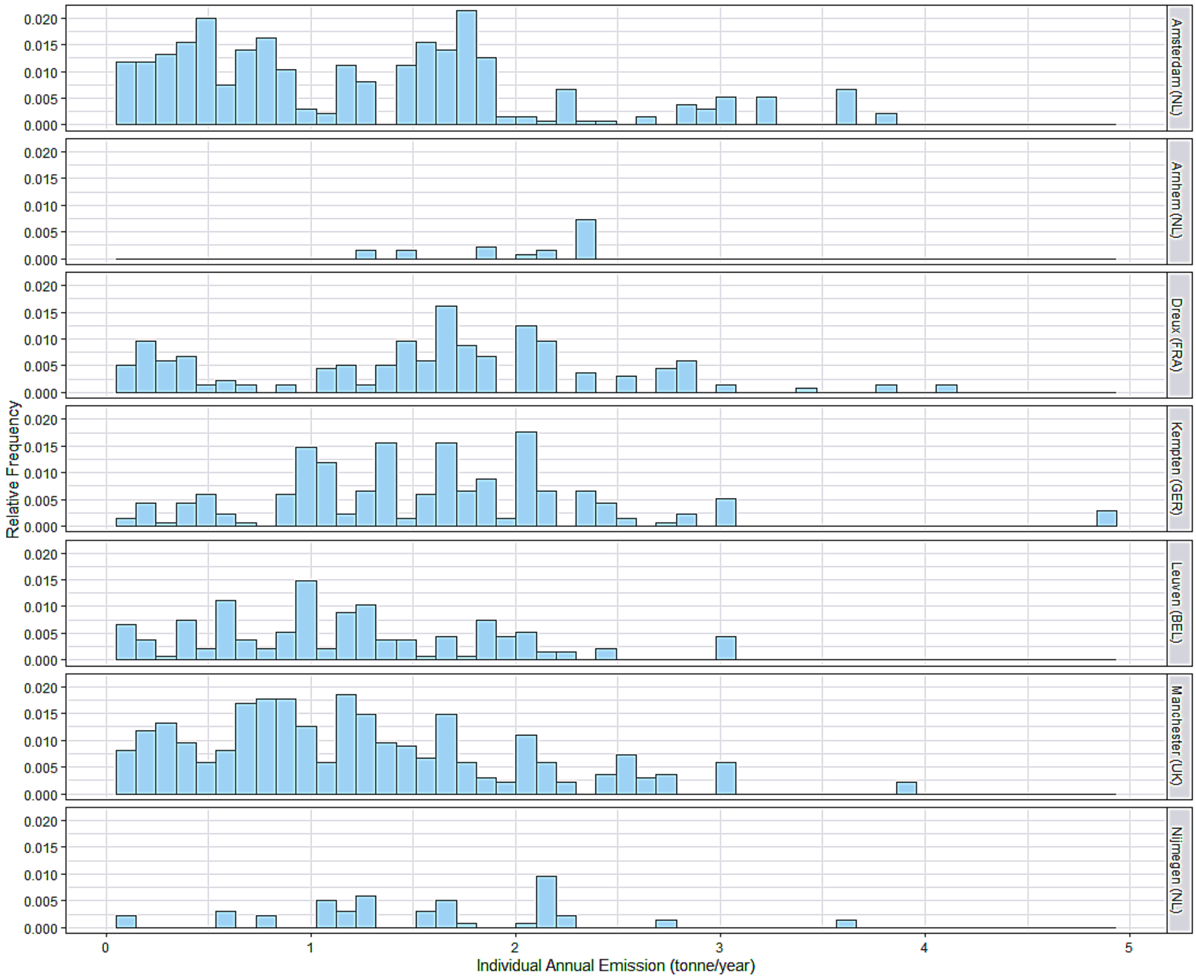


Figure 10. Distribution of individual's annual emissions (tonnes/year) of QS1 survey participant's journeys in each city

Figure 10 shows the distribution of individual's annual emissions across all eHUBS cities for QS1 survey. Amsterdam received 350 responses, with mean and median values at 1.27 and 1.19 tonne/year, respectively. Arnhem received 20 responses, with mean value at 2.03 tonne/year and median value at 2.25 tonne/year. Dreux got 192 responses, with mean and median values at 1.55 and 1.61 tonne/year, respectively. Kempten had 223 responses, with mean and median values at 1.58 and 1.59 tonne/year, respectively. Leuven received 161 responses, with mean value at 1.17 tonne/year and median value at 1.09 tonne/year. Manchester obtained 348 responses, with mean value at 1.21 tonne/year and median value at 1.13 tonne/year. Nijmegen had 62 responses, with mean value at 1.56 tonne/year and median value at 1.54 tonne/year.

Figure 11. Average annual emissions (tonnes/year) of QS1 survey participant’s journeys in each city

Figure 11 shows the average annual emission of all cities for QS1 survey. A comparison of the effect of the intension to use shared mobility services on annual emission across all eHUB cities showed that, a statistically significant difference in annual emissions between the different shared mode for Arnhem ($\chi^2(3) = 16.64$, $p < 0.001$), Manchester ($\chi^2(3) = 32.94$, $p < 0.001$) and Nijmegen ($\chi^2(3) = 10.79$, $p = 0.01$). Specifically, for Arnhem, with a mean annual emission of 2.32 tonne/year for the intension to use shared e-scooters, 2.32 tonne/year for shared bike, 2.04 tonne/year for shared car and 1.71 tonne/year for participants who are not interested to use any shared vehicles. The post hoc Dunn test showed that annual emission of no shared interest participants was statistically significantly lower to shared e-scooters (p=0.003) and shared bike (p=0.006). For Manchester, with a mean annual emission of 1.23 tonne/year for intension to use shared e-scooters, 1.95 tonne/year for shared bike, 1.96 tonne/year for shared car and 1.10 tonne/year for participants who are not interested to use any shared vehicles. The post hoc Dunn test showed that annual emission of no shared interest participants was statistically significantly lower to shared bike (p<0.001) and shared car (p<0.001). For Nijmegen, with a mean annual emission of 2.19 tonne/year for intension to use shared e-scooters, 0.60 tonne/year for intension to use shared bike, 0.82 tonne/year for intension to use shared car and 1.60 tonne/year for participants who are not interested to use any shared vehicles. The post hoc Dunn test showed that annual emission of no shared interest participants was statistically significantly higher to shared bike (p=0.03). For other cities, there was no statistically significant difference in annual emissions between the different shared mode. However, annual emissions produced by no shared interest participants were lower to shared e-scooters (Amsterdam), shared bike (Dreux, Kempten and Leuven).

Participants with intension to use shared mobility services may face some barriers to deter them from using eHUBS, such as the availability of shared vehicles, the distance of shared vehicles' location, price, safety, and effort required (Machado *et al.*, 2018). Because of these reasons, people continue to need to use drive their car for commuting, shopping and/or leisure, which results in high car-related annual and short-journey emissions. Therefore, if the shared mobility service provision could incentivise this group of potential users to overcome these barriers, they may be more likely to switch their car trips to shared alternatives, reducing their car-related emissions.

4.3 The effect of adopting shared mobility services on short journey/annual emission across all cities

Distribution of individual's short-journey emission across all eHUBS cities for QS2 survey is shown in **Figure 12**. Amsterdam received 27 responses, with mean and median values at 0.49 and 0.48kg/day, respectively. Arnhem received 46 responses, with mean value at 0.74 kg/day and median value at 0.92kg/day. Dreux got 29 responses, with mean and median values at 0.55 and 0.51kg/day, respectively. Kempten had 12 responses, with mean and median values at 0.36 and 0.46kg/day, respectively. Leuven received 123 responses, with mean value at 0.58kg/day and median value at 0.51kg/day. Manchester got 58 responses, with mean value at 0.59kg/day and median value at 0.54kg/day. Nijmegen had 118 responses, with mean value at 0.61kg/day and median value at 0.43kg/day.

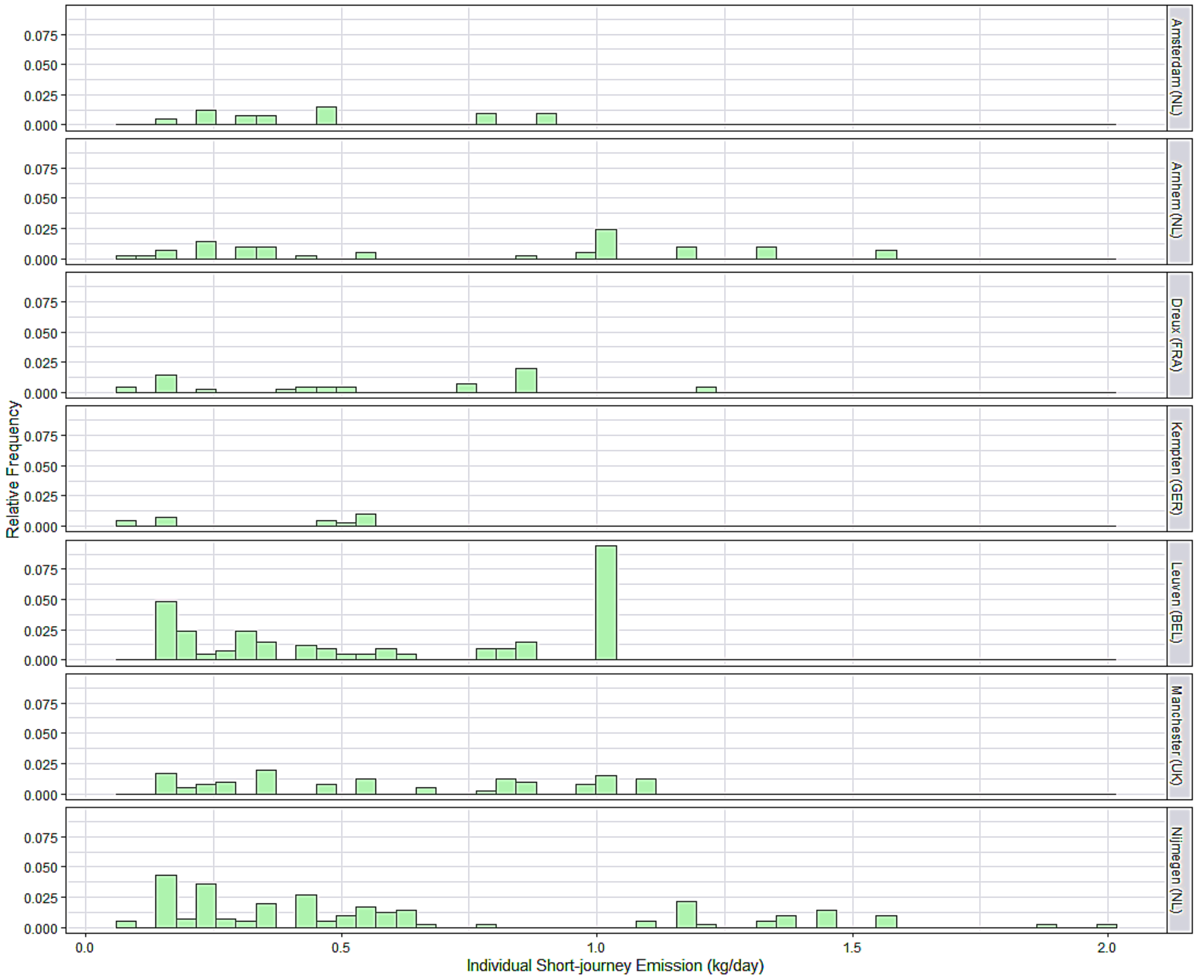


Figure 12. Distribution of individual's short-journey emissions (kg/day) of QS2 survey participant's journeys in each city

Average short-journey emissions of all cities for QS2 survey are shown in **Figure 13**. The short-journey emissions between users substituted car trip and non-users car trips, were compared, the mean value for users (1.32kg/day) was statistically significantly higher than non-users (mean of 0.69kg/day) (p=0.02). For Leuven, the mean value for users (0.81kg/day) was statistically significantly higher than non-users (mean of 0.40kg/day) (p<0.001). For other cities, there was not statistically difference in short-journey emissions between users substituted car trip and non-users car trips. For Amsterdam and Manchester, users substituted car trip produce higher number of short-journey emissions than non-users car trips. However, for Kempten and Nijmegen, users substituted car trip produce less emissions than non-users car trips.

Figure 13. Average short-journey emissions (kg/day) of QS2 survey participant’s journeys in each city

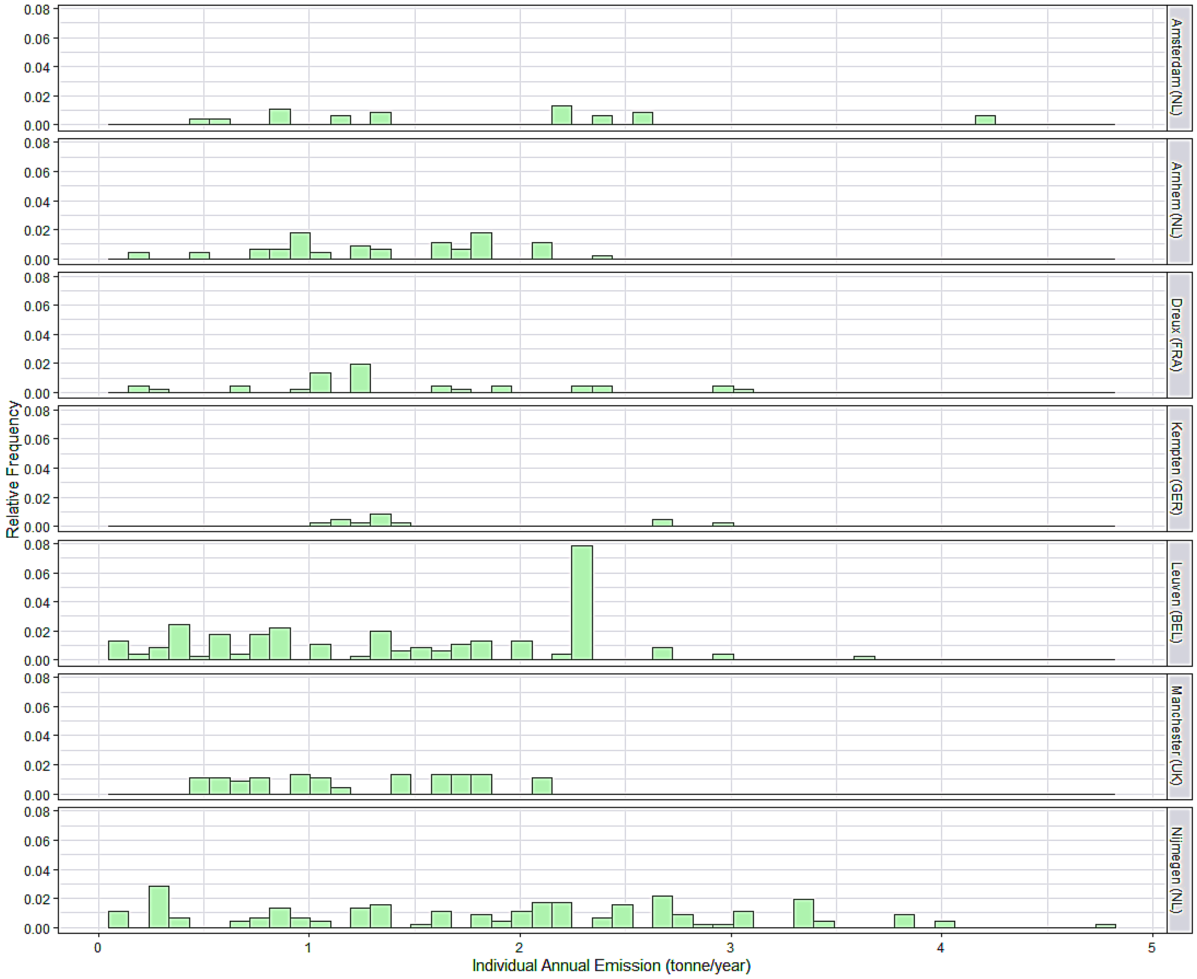


Figure 14. Distribution of individual's annual emissions (tonne/year) of QS2 survey participant's journeys in each city

The distribution of individual's annual emission across all eHUBS cities for QS2 survey is shown in **Figure 14**. Amsterdam received 32 responses, with mean and median values at 1.84 and 1.80 tonne/year, respectively. Arnhem received 49 responses, with mean value at 1.34 tonne/year and median value at 1.33 tonne/year. Dreux got 33 responses, with mean and median values at 1.44 and 1.23 tonne/year, respectively. Kempten had 12 responses, with mean and median values at 1.65 and 1.36 tonne/year, respectively. Leuven received 139 responses, with mean value at 1.44 tonne/year and median value at 1.45 tonne/year. Manchester obtained 51 responses, with mean value at 1.23 tonne/year and median value at 1.13 tonne/year. Nijmegen had 132 responses, with mean value at 1.88 tonne/year and median value at 2.05 tonne/year.

Figure 15. Average annual emissions (toone/year) of QS2 survey participant's journeys in each city

Average annual emissions of all cities for QS2 survey are shown in **Figure 15**. Annual emissions between users substituted car trips and non-users car trips were compared and for Leuven, the mean value for users (1.79 tonne/year) was statistically significantly higher than for non-users (mean of 1.22 tonne/year) ($p<0.001$), while for Nijmegen, the mean value for users (1.14 tonne/year) was statistically significantly lower than non-users (mean of 1.98 tonne/year) ($p<0.001$). For other cities, there was no statistically significant difference in annual emissions between users and non-users. However, for Amsterdam, Dreux, Kempten and Manchester, users produced fewer annual emissions than non-users.

Shared mobility services could reasonably replace the majority of short trips (<5 km) currently made by private car (Ciari and Becker, 2017). Users supposed to produce less car-related short-journey emissions compared to non-users. However, from our findings, only users from Kempten and Nijmegen produce fewer emissions than non-users. Limited sample size for users could be one possible reason to explain this finding. However, for most of cities, users produce less car-related annual emissions compared to non-users. As discussed by previous studies, shared mobility services could reduce car ownership and individuals’ annual vehicle kilometres(Machado *et al.*, 2018; Arbeláez Vélez and Plepys, 2021). All these changes can potentially reduce car-related annual emissions.

4.4 Individual carbon emission saving

Individual’s car-related emission was calculated based on the equation 3, which has been discussed in section 2.2.1. Users’ trip distances reported in QS2 survey ranged from 1.6 to 11.3km. Data of car trip frequency was based on previous studies at the country level. Specifically, average number of trips per person per day made by car is 2.26 in Belgium, 1.74 in France, 1.94 in Germany, 1.66 in Netherlands and 1.61 in the United Kingdom (Hubert *et al.*, 2008; Fiorello *et al.*, 2016; Raux *et al.*, 2016; Paffumi *et al.*, 2018; Follmer and Gruschwitz, 2019; Dft, 2020).The percentage of last trip substituted by shared e-vehicles was obtained from QS2 survey, where 39% car trips will be substitute by shared e-cars, 24% by shared e-bike and 67% by shared e-cargobike.

Emission factors of shared e-vehicles were calculated using shared e-vehicles energy efficiency multiplied by the specific emissions from electricity generation. The energy efficiency ranged from 0.15-0.20kWh/km for shared e-car, 0.005-0.02kWh/km for shared e-bike and 0.009-0.018kWh/km for shared e-cargobike (Lemire-Elmore, 2004; Narayanan and Antoniou, 2021; Virta Global, 2021).

The distribution of user’s emission before and after eHUBS and overall emission savings are shown in **Figure 16** and **Table 2**. Figure 16 shows huge variations in the differences between the e-mobility and the substituted trip. However, the average values of the emissions need to be treated with caution given that the sample size ranges from 4 through to 93. Ignoring Kempton given only 4 responses the savings in carbon ranged from 0.46 to 0.97kg/day and 0.17 to 0.35tonne/year. These values can be used to scale-up the emissions across wider areas. This was demonstrated in Manchester using the values 0.59kg/day and 0.21 tonne/year for daily and annual emission estimates respectively.

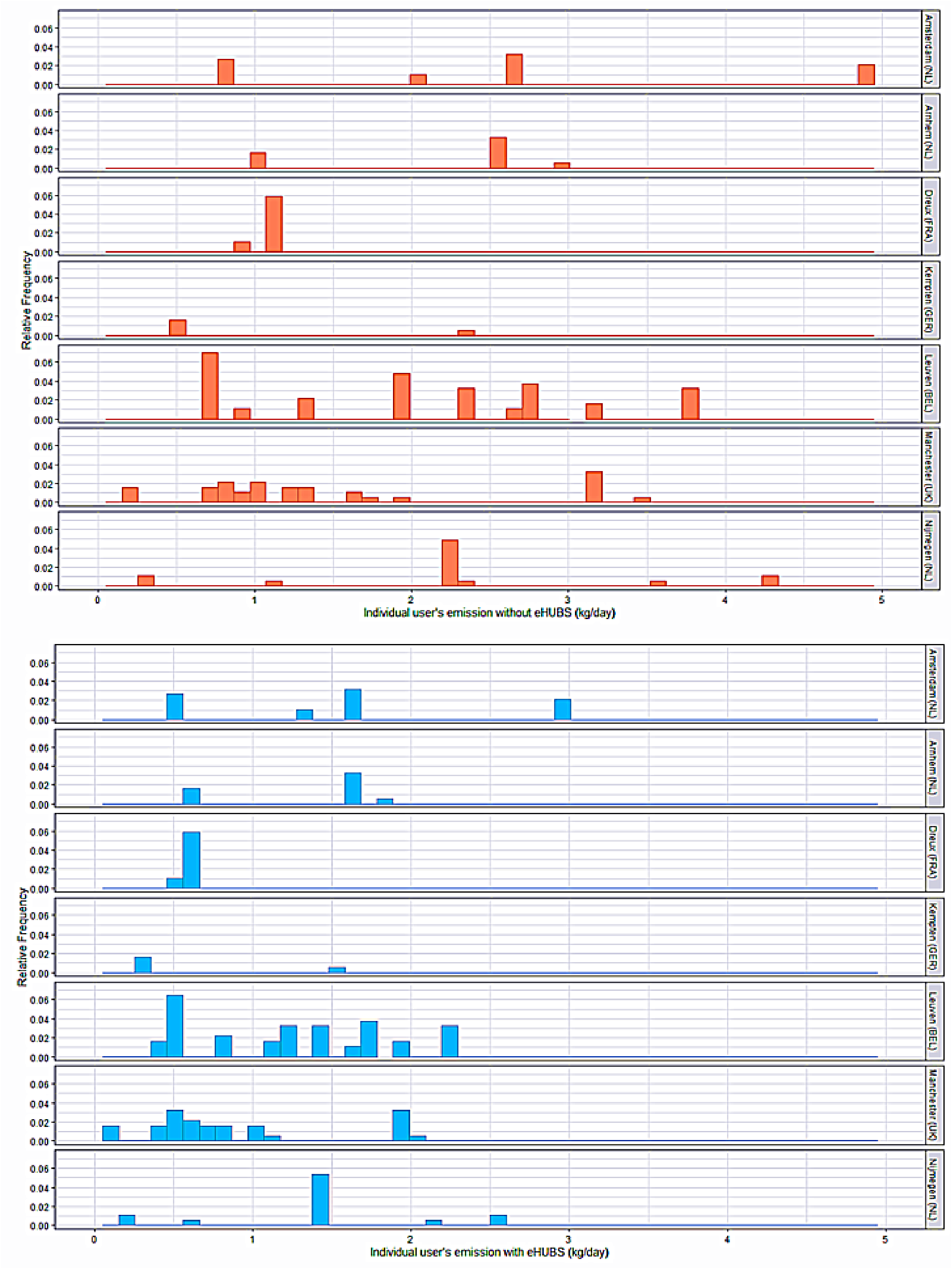


Figure 16. Distribution of shared mobility users' emissions before eHUBS (upper figure) and after eHUBS (below figure) of all cities

Table 2. Individuals' CO_2 emission change after adopting eHUBS of all cities

City	Sample Size	Without eHUBS (kg/day)	With eHUBS (kg/day)	Daily CO_2 Emission Saving (kg/day)	Annual CO_2 Emission Saving (tonne/year)
Amsterdam (NL)	17	2.57	1.59	0.97	0.35
Arnhem (NL)	10	2.14	1.34	0.80	0.29
Dreux (FRA)	13	1.09	0.63	0.46	0.17
Kempten (GER)	4	1.00	0.63	0.37	0.13
Leuven (BEL)	93	2.48	1.52	0.97	0.35
Manchester (UK)	33	1.48	0.90	0.59	0.21
Nijmegen (NL)	16	2.29	1.44	0.85	0.31

A Kruskal-Wallis H test showed that there was a statistically significant difference in saved emissions between different cities, $\chi^2(6) = 30.11$, $p < 0.001$. The biggest emission saving was observed for Amsterdam and Leuven, with average daily emission saving at 0.97kg/day. Leuven's saving is statistically significantly higher than Dreux (mean of 0.46kg/day, p=0.003), Kempten (mean of 0.37kg/day, p=0.02) and Manchester (mean of 0.59kg/day, p=0.002). However, Amsterdam's saving was not statistically significantly higher than other cities.

Figure 17 shows that users' emissions without eHUBS and with different modes of eHUBS of all cities. All these types of shared e-vehicles could contribute emission saving compared to without eHUBS. Users' car trips will be substituted by shared e-cargobikes more frequently compared to shared e-car and shared e-bike, therefore user using shared e-cargobike produce less emissions than shared e-car and shared e-bike.

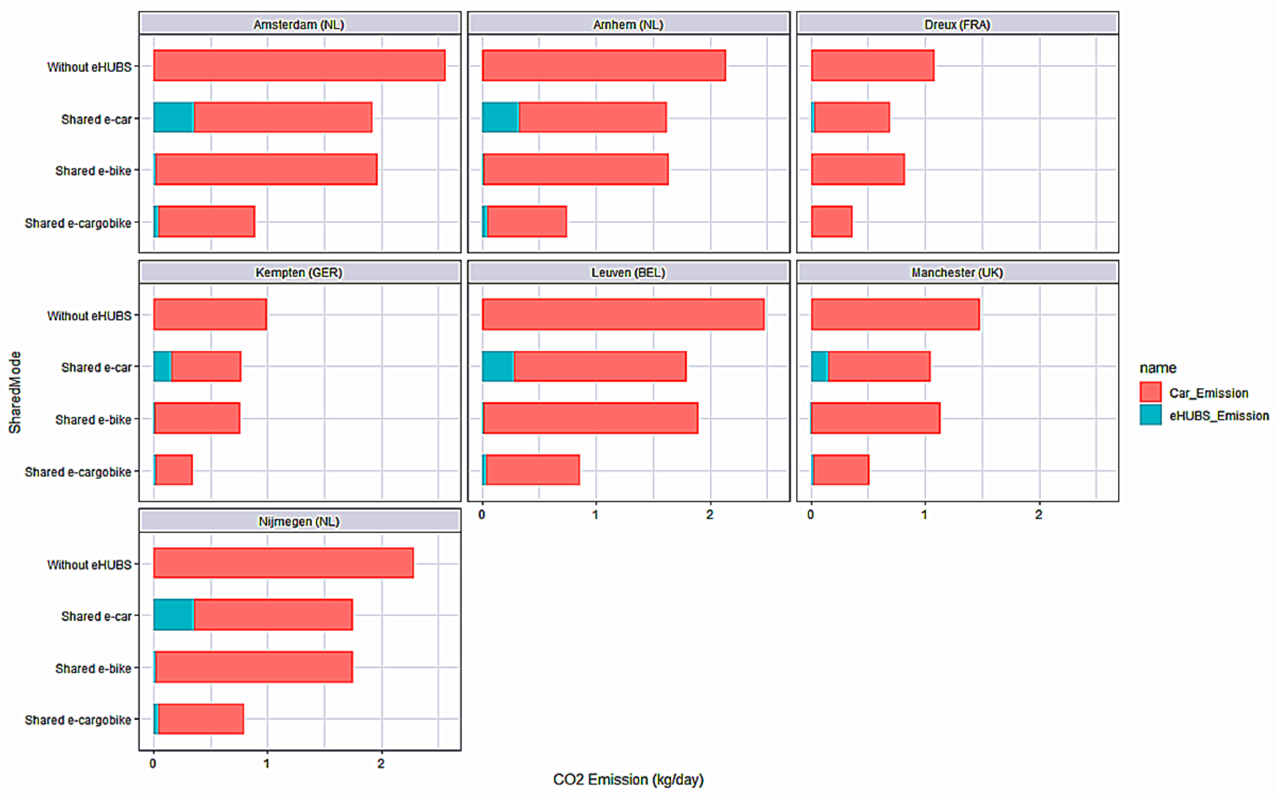


Figure 17. Shared mobility users' emissions without eHUBS and with different modes of eHUBS of all cities.

4.5 Individual toxic air pollutants emission saving

Users overall NO_x emission saving are shown in **Table 3**. A Kruskal-Wallis H test showed that there was a statistically significant difference in saved emissions between different cities, $\chi^2(6)=18.95$, p = 0.004.

Table 3. Individuals' NO_x emission change (g/day) after adopting eHUBS for each city

City	Sample Size	Without eHUBS (g/day)	With eHUBS (g/day)	Daily NOx Emission Saving (g/day)
Amsterdam (NL)	17	3.5	2.0	1.5
Arnhem (NL)	10	2.0	1.1	0.9
Dreux (FRA)	13	2.9	1.6	1.3
Kempten (GER)	4	0.5	0.3	0.2
Leuven (BEL)	93	2.5	1.4	1.1
Manchester (UK)	33	3.0	1.7	1.3
Nijmegen (NL)	16	1.8	1.0	0.8

Biggest emission saving was observed for Amsterdam, with average daily NOx emission saving at 1.5g/day. Manchester's saving takes second place with an average daily NOx emission saving at 1.3g/day, which is statistically significantly higher than Nijmegen (mean of 0.8g/day, $p=0.05$).

Users overall $PM_{2.5}$ emission saving are shown in **Table 4**. A Kruskal-Wallis H test showed that there was a statistically significant difference in saved emissions between different cities, $\chi^2(6) = 34.93$, $p < 0.001$. Biggest $PM_{2.5}$ emission saving was observed for Leuven, with average daily $PM_{2.5}$ emission saving at 80.9mg/day, which is statistically significantly higher than Amsterdam (mean of 59.7mg/day, $p=0.04$), Arnhem (mean of 51.8mg/day, $p=0.01$), Kempten (mean of 27.6mg/day, $p=0.02$), Manchester (mean of 61.6mg/day, $p<0.001$) and Nijmegen (mean of 61.1mg/day, $p=0.05$).

Table 4. Individuals' $PM_{2.5}$ emission change after adopting eHUBS for each city

City	Sample Size	Without eHUBS (mg/day)	With eHUBS (mg/day)	Daily $PM_{2.5}$ Emission Saving (mg/day)
Amsterdam (NL)	17	249	189	59.7
Arnhem (NL)	10	219	167	51.8
Dreux (FRA)	13	227	156	75.5
Kempten (GER)	4	116	88	27.6
Leuven (BEL)	93	331	250	80.9
Manchester (UK)	33	211	150	61.6
Nijmegen (NL)	16	250	189	61.1

Users overall PM_{10} emission saving are shown in **Table 5**. A Kruskal-Wallis H test showed that there was a statistically significant difference in saved emissions between different cities, $\chi^2(6)=39.95$, $p < 0.001$. Similar to $PM_{2.5}$, the biggest PM_{10} emission saving was observed for Leuven, with average daily PM_{10} emission saving at 102mg/day, which is statistically significantly higher than Amsterdam (mean of 75.9mg/day, $p=0.04$), Arnhem (mean of 66.3mg/day, $p=0.02$), Kempten (mean of 35.2mg/day, $p=0.02$), Manchester (mean of 71.6mg/day, $p<0.001$) and Nijmegen (mean of 77.0mg/day, $p=0.04$).

Table 5. Individuals' PM_{10} emission change after adopting eHUBS of all cities

City	Sample Size	Without eHUBS (mg/day)	With eHUBS (mg/day)	Daily PM_{10} Emission Saving (mg/day)
Amsterdam (NL)	17	442	366	75.9
Arnhem (NL)	10	391	324	66.3
Dreux (FRA)	13	320	236	83.2
Kempten (GER)	4	207	172	35.2
Leuven (BEL)	93	581	480	102.0
Manchester (UK)	33	331	260	71.6
Nijmegen (NL)	16	440	363	77.0

4.6 Scaling-up individual emission savings to geographic areas

Daily individual emission savings for CO_2, NO_x, PM_{10} and $PM_{2.5}$ are taken from Tables 2-5 for Manchester. For each area, the total number of households and those that are car-dependent families (Cluster 1) is taken from the Office for National Statistics dataset "LC4110EW - Car or van availability by household composition". This dataset is collected as part of the Census for England and Wales and covers areas of different geographic level from Lower Super Output Areas (LSOA), consisting of approx. 1,500 individuals, across the entire country of England. The potential emissions savings from Scenarios 1 and 2 are presented in **Tables 6 and 7**.

4.6.1 Scenario 1 Results

When assuming 100% of adults within car-dependent families will replace their main journey with eHUBS, the Greater Manchester area could benefit from savings in the region of 160,000kg of CO_2, 356kg of NO_x, 19kg of PM_{10} and 17kg of $PM_{2.5}$ a day.

Table 6 shows that there is not a uniform number of car-dependent families across each geographic area, for example whilst there are 160% more households in Manchester compared to Bury, there are only 80% more car-dependent families. This scenario assumes a widespread roll-out of eHUBS across each area where 100% of the households have access to the service, an alternative approach would be to target only the areas with the greatest potential to adopt eHUBS for the greatest return on investment.

Table 6. Emission saving with 100% eHUBS availability across entire area

		Total Potential Emission Savings			
Area (Geographic Level)	**Households (within Cluster 1)**	**CO_2 (kg/day)**	**NO_x (kg/day)**	**PM10 (kg/day)**	**PM2.5 (kg/day)**
England (Country)	22,063,368 (5,369,916)	3,170,000	7,030	385	331
Northwest (Region)	3,009,549 (718,115)	424,000	941	51.4	44.2
Greater Manchester (Metro. County)	1,128,066 (271,433)	160,000	356	19.4	16.7
Manchester (City)	204,969 (37,458)	22,000	49,000	2.6	2.3
Bury (Town)	78,113 (20,808)	12,300	27.3	1.49	1.28
Manchester 053E (LSOA Census Zone)	782 (172)	101	0.225	0.0123	0.0106

4.6.2 Scenario 2 Results

The choropleth map in **Figure 18** indicates the proportion of car-dependent families broken down to each LSOA of Greater Manchester, and therefore potentially the areas with the highest propensity to adopt eHUBS and the biggest emissions savings. Clearly, there is much variation across Greater Manchester with a tendency for the outer suburbs of Manchester to have the highest proportion of car-dependent families and less present in Manchester city centre.

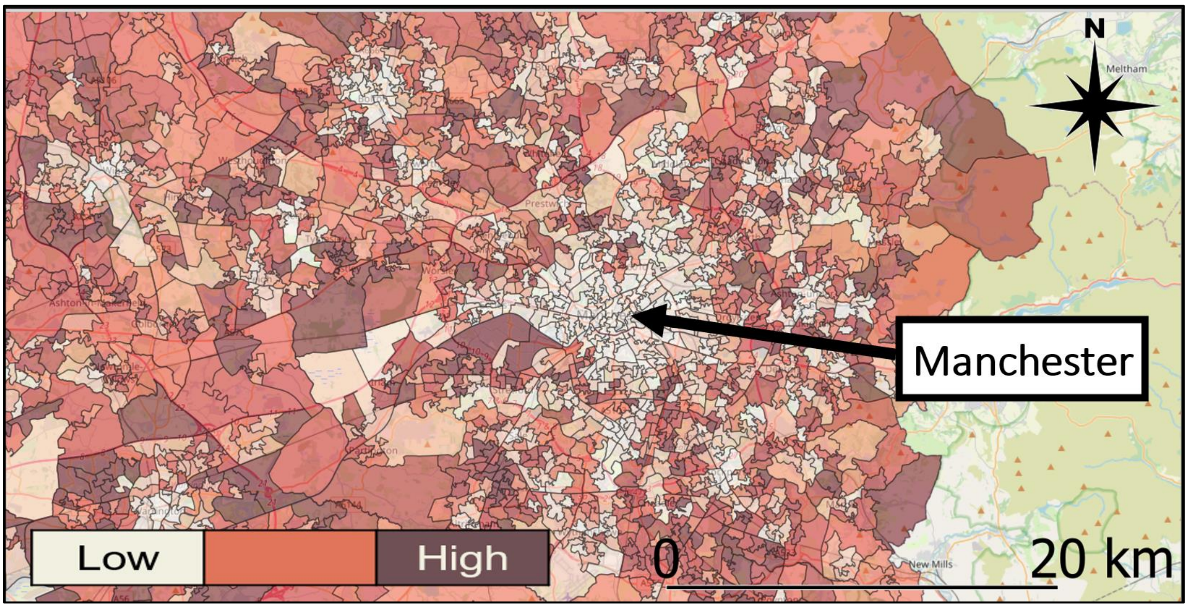


Figure 18. Greater Manchester LSOA mapped by Proportion of Cluster 1 Households

Once the proportion of car-dependent families for each of the LSOA zones was determined, those with the highest proportions of car-dependent families were selected, creating a dataset of approximately 20,000 households to test Scenario 2, representing about 10% of the households in Manchester (204,969). Similarly, the LSOA zones with the lowest car-dependent families were selected.

A comparison of the potential emission savings of the top 10% LSOA and lowest 10% LSOA of the population, as well as the average across Manchester, is shown in **Table 7**. The benefit of targeting areas with higher proportions of Cluster 1, the car-dependent family, is apparent as ten times as many of the early-adopting car-dependent families are located in these areas compared to the low propensity area, and twice as many as the average across Manchester.

Table 7. Scenario 2 - Emission Savings targeting areas of highest propensity within Manchester

		Total Potential Emission Savings			
eHUBS propensity / Scenario	**Households (within Cluster 1)**	**CO_2 (kg/day)**	**NO_x (kg/day)**	**PM10 (kg/day)**	**PM2.5 (kg/day)**
Manchester - High Propensity Areas	20,546 (6,127)	22,100	49.1	2.68	2.31
Manchester - Mean Average	20,000 (3,660)	3,620	8.03	0.439	0.377
Manchester – Low Propensity Areas	20,471 (497)	293	0,651	0.0356	0.0306

4.6.3 Summary of Scaling-up Results

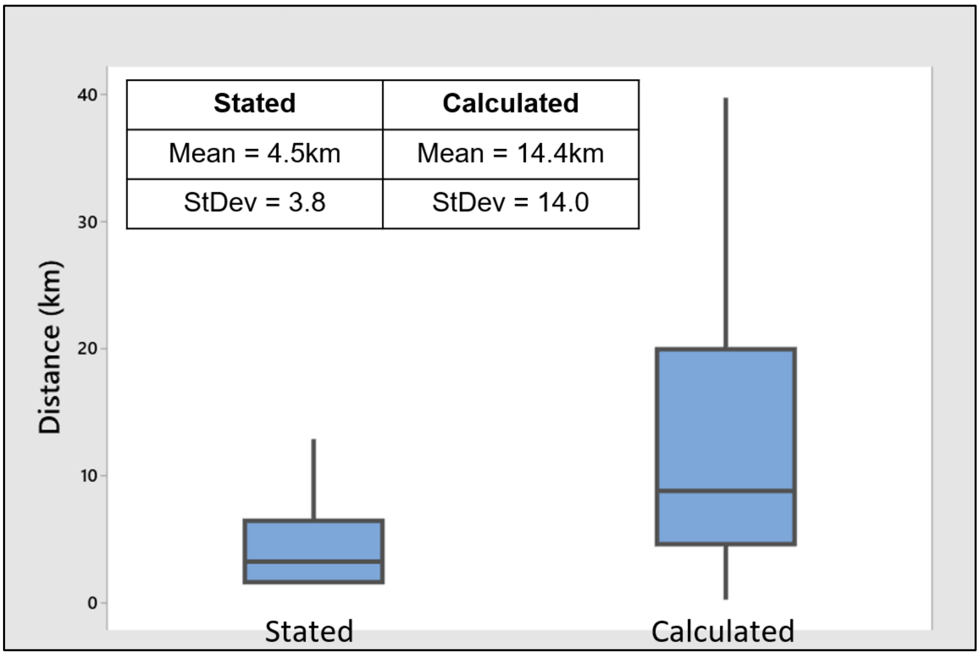
Tables 6 and 7 show the forecasts for total potential emission savings are strongly dependent on which scenario is being tested, and thus will improve as do the accuracy of the scenarios. This will occur through greater understanding of policies and targets to be set for the uptake of eHUBS. **Table 7** shows how a more realistic policy that targets areas with the highest propensity to adopt eHUBS (scenario 2) will produce significantly different results than a policy where there is uniform rollout (Scenario 1) of the service across a city or region.

4.7 Limitations

Due to the limited sample size of eHUBS users, further investigation requires repeating the analysis with a larger sample size.

4.7.1 Limitations with stated distances used in individual emission saving

As trip distance plays a key role in the emissions produced, it was decided to test whether there was any statistically significant difference in the distances that respondents stated they travelled and the actual distances revealed by the origin – destination (O-D) postcodes they also submitted. At the time of the analysis, there was insufficient postcode data within the eHUBS-user responses in the QS2 survey data, so the test was carried out on the earlier QS1 non-user survey O-D data was routed through Open Street Maps using the Geographic Information System software, QGIS, to calculate the actual distance of each reported individual trip. The results showed that there was a statistically significant difference in the distance travelled compared to that reported by the responders. The two-sample *t*-test confirmed that there was a statistically significant difference between the stated and calculated trip distances (P-Value < 0.001), with a sample size of 243. Calculated trip distances on average were 320% further than the those stated by respondents to the survey.



Stated	Calculated
Mean = 4.5km	Mean = 14.4km
StDev = 3.8	StDev = 14.0

Figure 19. Boxplots comparing stated and calculated distances

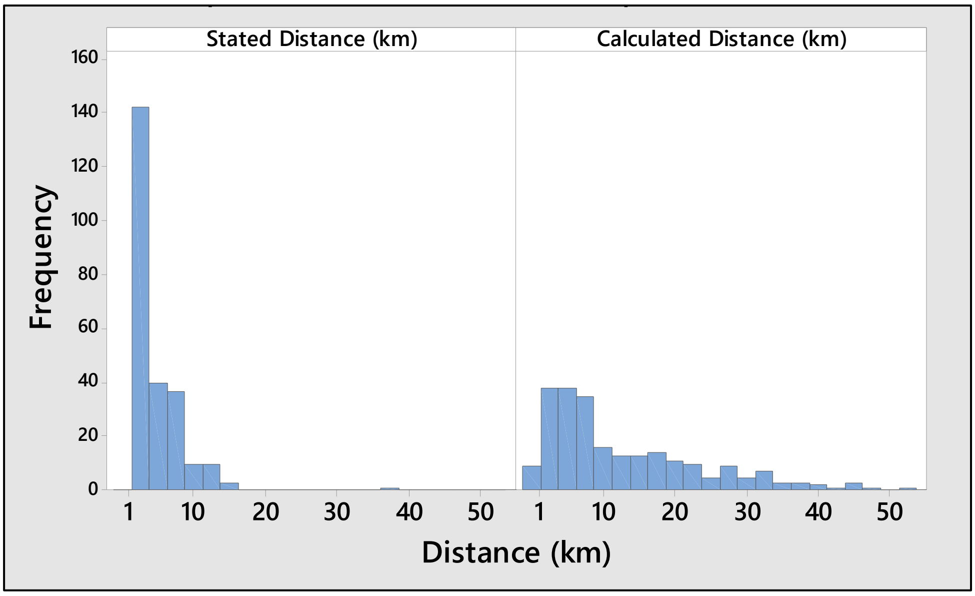


Figure 20. Histogram comparing stated and revealed distances

The histogram in **Figure 20** shows that there is a high frequency of individuals with trip distances falling within the shortest trip distance bin. On inspection of the data, it appears that many of the respondents were stating that their typical journey was exactly 1 mile (1.6km) long, when in fact after routing the O-D data through the network it was much higher. It may well be that some respondents are unaware of the distances they are travelling and this should be taken into consideration for any future emission calculation based on stated travel distances.

4.7.2 Limitations with criteria for scaling-up exercise

Like most scaling up exercises, assumptions need to be made. Limitations include disregarding the population that did not fall within the 'Cluster 1' respondents, i.e., those that are not car - dependent families. However the focus on this particular demographic was justified as this emerged from the research of Bösehans *et al.* (2021), that found that individuals from car-dependent families are the likely early adopters of eHUBS whilst also possessing the greatest potential for emission savings. However, individuals outside of this demographic may still wish to switch to eHUBS when presented with the opportunity. Similarly, as mentioned in Section 2.3, the creation of eHUBS uptake scenario 1 (100%) within the Cluster 1 demographic could be calibrated to reflect policies or targets that are set in the future by local / national governments. Additionally, the UK Census is recorded every 10 years and whilst the last Census was collected in 2021, this data is not fully available therefore, the most recent dataset for household composition and car ownership dates back to 2011. There may have been changes since that data was collected.

5. Conclusion

The shared mobility services are considered fundamental to sustainable development in urban mobility due to its low CO_2 emissions. Moreover, this e-mobility technology helps to increase multimodality travel, avoids or delays vehicle ownership, vehicle miles/kilometres travelled (VMT/VKT), all of which can potentially reduce car-related emissions. In the first investigation, 26% car users who intended to use shared mobility services, whether shared-bike, shared-car, or shared e-scooters. However, they were shown to produce a high number of short-journey and annual emissions compared to people who are not willing to use this technology. Possible reasons, stopping the use of shared services to replace their regular car trips include financial, convenience, lifestyle and safety. Therefore, the shared mobility providers and the policy makers should consider the specific needs of this group of potential users and take steps to overcome these barriers. From our second investigation, shared mobility users were found to produce less car-related annual emissions compared to non-users tending to substitute shorter trips. However, by using shared mobility services car ownership is delayed or avoided, and individuals' annual vehicle kilometres are reduced, all these can potentially help eHUBs users reduce their car-related annual emissions. Additional benefits that occur by removing the shorter trips is that congestion and associated additional emissions are likely to reduce. Moreover, from the user survey, for all eHUBs cities, individuals' substituted some, rather than all, of their trips to shared mobility contributing to the reduction of car-related.

The scaling-up exercise demonstrates a methodology that considers the segments of the population that are most likely to adopt eHUBS as a method of travel. Moreover, the method is easily transferred to anywhere in England and at any geographic level. Also the approach is readily applied to other countries wishing to roll out eHUBS provided the equivalent of Census data is available. The total potential CO_2, NO_x, PM_{10} and $PM_{2.5}$ emission savings were found to be strongly dependent on which scenario is being tested and these should be aligned with policies and targets set by governments in the future. Additionally, the emission saving estimates will become more accurate with knowledge of how eHUBS will be implemented spatially, as the difference between uniform rollout across a city or region will produce statistically significantly different results (factor of six times less) than a policy that targets those areas with the highest propensity to adopt eHUBS.

Finally given the differences found in the reported and actual origin-destination distances suggested that respondents were likely to be reporting shorter single journeys (from the bus/railway station) or additional round-trips made during the day which are precisely those trips for which eHUBS services are being used as designed. However, the results also suggest there is much potential to extend the eHUBS services to provide the ‘first/last mile’ services integrated with public transport with potential to achieve over three times higher levels of toxic and carbon emissions reductions.

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