Calculating Carbon Emissions from Personal Travelling: Insights from a Top-Down Analysis of Key Calculators

Girish Bekaroo[1,*], Divesh Roopowa[1], Abubakar Zakari[2], Debbie Niemeier[3]
[1]School of Science and Technology, Middlesex University Mauritius, Mauritius
[2] Faculty of Computer Science and Information Technology, University of Malaya, Malaysia
[3]A.James Clark School of Engineering, University of Maryland, United States
Email of corresponding author: g.bekaroo@mdx.ac.mu

Abstract: Personal travelling unfavourably contributes to the emissions of greenhouse gases, which adversely causes long-term damage to the climate. In order to reduce the associated negative impacts of such activities on the environment, there is a wide consensus that enhancements and innovations in the efficiency of vehicles will not be enough, but behavioural changes are needed. For this, individuals should be able to measure their travel-related carbon emissions and such emissions could be determined by using personal carbon footprint calculators, which proliferated during the previous decade. However, various research questions related to such calculators are yet to be answered in published literature. As such, this paper investigates how key transport-based calculators account for emissions from personal transport-related activities following a top-down analysis. In this endeavour, ten such calculators are investigated through a set of formulated research questions to analyse their scope, calculation approach used, transparency, consistency of results, communication methods utilized and platform differences. Results revealed that the calculators have varying granularity, limited transparency, provide significantly inconsistent results in some cases and are not fully engaging end-users. Based on limitations identified, recommendations have been proposed through a taxonomy to guide policy makers towards improving such tools.

Keywords: *Personal Travelling, Carbon Footprint Calculators, Carbon Emissions, Top-Down Analysis, Taxonomy of Recommendations.*

1. INTRODUCTION

Transport, which refers to the movement of people, animals or goods from one place to another, is considered as a non-separable part of the contemporary society. It is a fundamental component for economic growth and human welfare, encompassing key categories including air, road, rail and marine transportation. In order to meet the needs of highly mobile and dispersed populations, hundreds of modes of transportation have been designed and developed for use by human beings (U.S. Department of State, 2014). Transportation activities have rapidly increased around the world (Uherek, et al., 2010; Wang, et al., 2011; Ribeiro, et al., 2007; Arora, et al., 2011; Dargay, et al., 2007) and robust growth in the sector is also expected to continue during the coming decades (Yan, et al., 2014). Among the transportation activities, personal travel has grown significantly in many countries around the world, particularly due to an increase in car ownership, decrease in costs of motoring and reduced car occupancy levels, among other reasons (Brand & Boardman, 2008). However, such growth also impacts the environment, notably through emissions of greenhouse gases (GHG) (Kobayashi, et al., 2007; Yan, et al., 2014). Whilst transport represents 27% of global GHG emissions (EPA, 2015), emissions from personal travel were found to increase steadily in both developed and developing countries during recent years (Brand & Boardman, 2008; Wadud, 2011; Xiao, et al., 2017; Han, et al., 2017). This is mainly because personal transportation is significantly dependent on petroleum, which is a principal source of carbon emissions (Wadud, 2011). Moreover, such emissions have also been predicted to increase by 80% between 2007 and 2030 (Woodcock, et al., 2009). As such, due to the significance of associated impacts of carbon emissions from personal transport-related activities (Hughes, 2013; Gül, et al., 2009), actions towards effectively reducing such emissions has become necessary (Brand & Boardman, 2008).

In the realm of transport, there is a wide consensus that enhancements and innovations in the efficiency of vehicles will not be enough to reduce associated impacts on the environment but behavioural changes are needed (Raux, et al., 2015; Edenhofer, et al., 2014). For this, individuals should be able to measure their transport-related carbon emissions as it is challenging to manage what cannot be measured (Curtis, 2008; Bekaroo, et al., 2014). To address this issue, personal carbon footprint calculators could be utilized. These are web-based tools or mobile applications that estimate the carbon footprint of individuals and provide advices on how personal emissions could be reduced (Birnik, 2013). Even though various such calculators are available on the market, limited work has been undertaken to analyse how such tools account for personal carbon emissions from transport-related activities. One such work has been conducted by Padgett, et al. (2008) to examine similarities and differences among ten US-based calculators. Although this study revealed intuitive information related to methods used and consistency of results among the studied calculators, the focus of the work was not directly on personal travelling (Padgett, et al., 2008). In addition, mobile-based calculators were not considered as part of the study. In another study, an evaluative framework encompassing of scope, methods, transparency, consistency and effectiveness of communication was used to analyse eight carbon calculators for food consumption (Kim & Neff, 2009). Even though this study as well exposed meaningful information related to the aspects analysed as part of the evaluative framework, its focus was on personal diet rather than personal travel. In addition, the opportunities and limitations of carbon calculators were investigated through the examination of ten such tools, while also interviewing six calculator hosts (Salo, et al., 2019). Nevertheless, this study did not directly focus on emissions from personal travelling, even though findings were insightful and showed that engaging people to utilize such tools is challenging.

As such, given the role of carbon calculators in instructing the general public and suggesting priorities for behavioural change related to personal travel, this paper aims at extending previous research on carbon footprint calculators to critically analyse how such tools account for emissions from personal transport-related activities before recommending how limitations could be addressed. The findings revealed in this study are expected to help policy makers, calculator designers and researchers in the field of low-carbon transportation to better understand limitations of personal transport-based carbon footprint calculators and effectively design solutions to address these shortcomings based on recommendations made in this paper.

2. Personal Transportation-Related Activities and Emissions of Carbon

Human beings personally contribute to the emissions of carbon dioxide via their transportation activities, for example, when travelling to work, for shopping or even travelling to an international destination for holidays. Two fundamental factors that influence the amount of CO_2 emitted include the travel pattern of the individual and the mode of transport utilized. Travel pattern or behaviour relates to how individuals travel and this factor was found to differ according to demographics, ethnicity, culture and socio-economic aspects (Brand & Boardman, 2008). On the other hand, different modes of transport utilized by individuals have varying contribution on their personal carbon emissions (Rothengatter, 2010). The common modes of transport along with their associated emissions of CO_2 are discussed as follows:

2.1 Road Transport

Road transport is considered as the biggest producer of greenhouse gases within the transport sector, representing approximately three quarters of the emissions (IEA, 2009; Raux, et al., 2015). As a central component of the modern society, road-based transportation encompasses human mobility, distribution of products manufactured and the provision of services such as collection of used materials and waste (Coelho, et al., 2015; Coelho, et al., 2016). For this type of transportation, crude oil is the dominant fuel source accounting for 81% of total energy use, with gasoline and diesel being the most common fuels utilized (Chapman, 2007). According to the same source, the combustion of such petroleum-based fuels in internal combustion engines produces a considerable amount of carbon and this amount is directly proportional to the amount of fuel being consumed by an engine. For instance, it was indicated in a previous study that CO_2 emissions of an average car consisted of 76% from fuel utilization and 15% from losses in the fuel supply system of the vehicle (Potter, 2003). Previous works have highlighted that human beings have become increasingly dependent on the use of private cars, where a quarter of all car trips made are actually less than two miles (Mackett, 1999; Ryley, 2001). Furthermore, 60% of total emissions from road-based transportation are sourced from personal vehicles (Wadud, 2011). Consequently, personal road transport sector is regarded as one of the largest and fastest growing sources of CO_2 emissions (Han, et al., 2017). Additionally, over the last 60 years, the global passenger vehicle fleet has grown annually by about 5%, representing approximately 900 million vehicles in the year 2013 and this fleet is expected to increase to 1.7 billion vehicles by the year 2035 (IEA, 2011).

2.2 Air Transport

With the increase in disposable incomes and awareness of the importance of leisure, the number of tourists has been growing during the previous years (Su & Lin, 2014). According to the World Tourism Organization (WTO), the number of international tourist arrivals increased from 538 million in 1995 to 1.2 billion in 2016, and is expected to reach 1.8 billion by 2030 (UNWTO, 2016). As such, air transportation also plays an important role in economic development and contributes to quality of life by enabling movement of people all over the globe (Yılmaz, 2017). It is one of the world's fastest growing means of transport (Ribeiro, et al., 2007; Chiu & Yeh, 2017). However, on the adverse side, aviation activity is also a major contributor of carbon emissions and contributes to approximately 2% (689 million tonnes of CO_2) of global anthropogenic CO_2 emissions (Air Transport Action Group, 2018), while also being the second largest emitter after road transport within the transport sector (Chapman, 2007). Emissions from aircrafts source principally from fuel burnt in the vehicle's engines to produce the GHGs (Yılmaz, 2017). On a global basis, the airline industry consumes over five million barrels of oil per day and carbon emissions from aircraft engines are relatively proportional to the fuel being used and therefore can progressively become a dominant source of CO_2 emissions (Grote, et al., 2014). As such, its future growth is likely to be accompanied with increasing emissions, although mitigation measures such as improved fuel efficiency are being implemented (Sgouridis, et al., 2011).

2.3 Rail Transport

Railway is a widely used means of transport across many countries and is mainly meant for carrying passengers between various remote cities, for high-density commuter transport and for long distance freight transportations. Much of the rail system is run using diesel, although other fuels could be utilized (WBCSD, 2001). In Europe and Japan, electricity is used as a major energy source to power rail systems, while in other countries like North America, fossil-based fuels are mostly utilized as prime energy source (Ribeiro, et al., 2007). Although railway requires a dedicated infrastructure, increasing the number of light rail schemes which are powered from overhead cables have reduced emissions at source and can in turn offer a cost effective solution on routes with the highest traffic and passenger flows (Chapman, 2007). Moreover, strategies have been investigated to further reduce the carbon footprint of rail systems during different stages of the life-cycle, including infrastructure construction and operation (Chester & Horvath, 2012). Overall, wheel on rails are considered as an ecologically aware form of transportation whilst being four times more efficient than road transport for passengers and two times as efficient for freight (Bonnafous & Raux, 2003).

2.4 Marine Transport

Marine transportation is considered as the dominant transport mode for overseas freight (Chapman, 2007). During recent years, there has been an increasing number of cruise ship vessels carrying passengers internationally between countries (Howitt, et al., 2010). As compared to planes, cruise ships include various additional services in the form of accommodation, catering and leisure facilities, thereby consuming fuel for both transport and to generate electricity for the services provided on-board (Becken & Hay, 2007). Furthermore, between one third and half of people on board of a cruise ship are members of the crew, thus significantly increasing the personal carbon emissions per passenger on the ship (Dickinson & Vladimir, 2007). With approximately 2.7% of world's total CO_2 emissions sourcing from international shipping principally due to burning of oil (Buhaug, et al., 2009), the International Maritime Organization (IMO) has recently initiated research and discussions on the mitigation of GHGs which are emitted by the shipping industry (Coelho, et al., 2015). As such, technical measures from the IMO is targeted to reduce carbon emissions by around 5% to 30% in new ships and by 4% to 20% in old ships. These reductions in carbon emissions can be realized by using current energy-saving technologies pertaining to hydrodynamics and machinery on new and existing ships (Ribeiro, et al., 2007). In addition, the use of cleaner fuels, such as gas, can significantly decrease ship emissions by 90% and shipping could also be ideal via the use of fuel cells (possibly as a hybrid), since the bulk and size of these cells would be less relevant on a ship (Chapman, 2007).

2.5 Estimating Carbon Emissions from Personal Transport through Carbon Footprint Calculators

As reliance on personal transport-related activities from the different modes appears to be causing long term damage to the climate (Duncan & Youngquist, 1999), quick decisions are utmost essential so as to reduce associated impacts on the environment (Chapman, 2007), and this could be facilitated through the use of personal carbon footprint calculators. The term 'personal carbon footprint', which relates to the amount of carbon dioxide emitted from the daily activities of individuals, has gained much popularity during the past decade (Wiedmann & Minx, 2008; Matthews, et al., 2008; Gao, et al., 2013). It has also been referred as a methodology to estimate the total emission of greenhouse gases (Carbon Trust, 2006; Fang, et al., 2014). Based on such methodology, there has been a proliferation of carbon footprint calculators during recent years, that provides individuals with the technological tools for estimating their carbon footprints (Birnik, 2013). The use of such calculators was found to enhance knowledge and understanding of environmental sustainability related aspects, in addition to impacts of unsustainable resource utilization (Collins, et al., 2018). These calculators are mainly sponsored by a wide range of organizations, which includes carbon-offset providers, private companies, environmental NGOs, local and national government authorities, universities and energy industries. These tools also remove the focus away from governmental responsibilities to mitigate the growth of GHG emission and put more emphasis on the responsibility of individuals (Paterson & Stripple, 2010). Despite their crucial roles on raising awareness, till date there has been no agreed consensus on how carbon footprints should be calculated and hence, most of the calculators vary in terms of their structures, input requirements and even their results can be different for the same data input (Kenny & Gray, 2009; Murray & Dey, 2009; Padgett, et al., 2008; Pandey, et al., 2011). Different models have been proposed for capturing and estimating carbon emissions from the modes of transportation, and previous studies highlighted that the modelling approaches infer assumptions (e.g. driver behaviour, fuel consumption converting to CO_2) (Linton, et al., 2015; Demir, et al., 2011). According to the same studies, two sets of assumptions principally influence the efficacy of such models, where the first one relates to the way in which the model represents the transport system and the second assumption is about the detailed algorithm and emission factors used to determine the emission estimates. Furthermore, in the past, proliferation of carbon footprint calculators was principally on the web platform. However, with the recent widespread adoption of smart phones to such an extent that these devices have already exceeded the number of people present on the planet (Boren, 2014), there has been the release of different personal carbon footprint calculators on the mobile platform. Nevertheless, as discussed earlier, with limited work undertaken about how these calculators account for personal transport-related activities, this aspect becomes essential to study. The research framework used for this investigation is discussed in the next section.

3. RESEARCH FRAMEWORK

In order to investigate how existing carbon calculators account for personal travelling, a top-down analysis of such tools is conducted in this study. For this, an adapted framework utilized in two previous studies (Padgett, et al., 2008; Kim & Neff, 2009) involving comparison of carbon footprint calculators was adopted. The reason for choosing these studies was that among the limited relevant studies, both works involved top-down analysis of existing carbon calculators, in which different comparison criteria were used. In this adapted framework, research is conducted in four stages. The first stage involves identification of the comparison criteria to be used, followed by formulating the research questions to be investigated for each identified comparison criterion. Then, the methodology used for analysing each comparison criterion is formulated to eventually select the transport-related calculators for review. These stages are further discussed as follows:

3.1 Comparison Criteria

For analysing carbon calculators, different comparison criteria were identified based on previous studies (Padgett, et al., 2008; Kim & Neff, 2009). These criteria are as follows:

- ***Scope***

Scope encompasses the categories and parameters that are accounted for in relation to transport-related emissions such as the vehicle model, engine type, year, fuel type, the total distance travelled by both private and/or public vehicle, among others. This criterion is essential in the analysis process since investigating the way different calculators are categorizing travel-related carbon emissions on top of emissions variables can reveal essential information about inconsistencies and limitations. As part of the analysis, a reasonable number of such categories are important since calculators having a small number of such categories means that emission related factors are not split enough. On the other hand, many categories are challenging to manage by end users and can make the calculation process lengthier.

- ***Calculation approach***

Calculation approach relates to the method used for calculating carbon emissions from personal travel. Analysing this criterion could help in understanding about how each tool is calculating carbon emissions and whether there is adherence to any international assessment standard. Furthermore, it can help to enlighten on the accuracy of estimation provided by travel-based carbon calculators.

- ***Transparency of approach***

Transparency relates to whether methods, emission-related parameters (e.g. emission factors) used by the calculators are published for consultation by end users. Similar to calculation approach, transparency helps calculator users to understand the emission-related parameters along with the formulae utilized. Moreover, improved transparency also makes peer-review process simpler such that reviewers (e.g. researchers, regulatory organizations and the public) could more easily provide appropriate feedback on computed emissions.

- ***Consistency of results***

This criterion relates to whether calculation results provided by the calculators are consistent or coherent. It helps to understand the accuracy of results, to identify inconsistencies and to comprehend factors rendering such results incoherent.

- ***Communication methods***

This aspect relates to the approaches being utilized by carbon calculators in order to convey key information on transport-related carbon emissions and reduction mechanisms. This criterion is important to study in order to understand how such tools are promoting knowledge and are encouraging steps towards behavioural change with regards to transport-related emissions. Different such approaches that were reviewed include:

1. Reporting on sources and causes of carbon emissions from transport systems.
2. Provision of generalised or customised information on transport-related carbon emissions reduction mechanisms.
3. Availability of mechanisms to track and analyse transport-related carbon emission trends.
4. Regularity of communication to engage end-user.

5. Additional engagement mechanisms involved including newsletters, emails, live chat and notifications.

- ***Published Platform***

Since the platform for rendering information and interaction is essential for improved adoption of carbon footprint calculators, this aspect becomes important to study as well. Platform here relates whether the carbon footprint calculator is web-based or a mobile application.

3.2 Research Questions

For each comparison criterion described earlier, specific research question(s) were formulated in order to better structure the comparative analysis. These research questions are given in Table 1.

Table 1 - Summary of Research Questions

Comparison Criterion	**Research Question**
Scope	RQ1: How does the categorization of transport-related emission parameters vary amongst selected calculators? RQ2: What variables are considered by personal carbon footprint calculators when computing transport-related carbon emissions?
Calculation approach	RQ3: What approach do the selected calculators utilize in order to calculate personal transport-related carbon emissions?
Transparency of approach	RQ4: How transparent are the calculation approaches and parameters for each calculator?
Consistency of results	RQ5: Are the results for transport-related emissions consistent across different carbon calculators? In case there are variances, what are their significance?
Communication methods	RQ6: How effectively are the transport-related emissions results conveyed to the users so as to promote awareness and encourage steps in behavioural change with regards to transport-related activities?
Platform	RQ7: How do RQ1-RQ6 vary for web-based and mobile-based platforms?
All criteria	RQ8: How could transport-based carbon calculators be improved based on limitations identified in RQ1-RQ7?

By answering RQ1-RQ8, this paper aims at making two contributions to literature. As first contribution, insights from a comparative analysis of existing calculators are provided based on application of the above research framework. Secondly, by answering RQ8, recommendations are proposed towards improvement of transport-based calculators for further investigation by the research community.

3.3 Methodology for Answering Formulated Research Questions

In order to answer RQ1 and RQ2, an analysis of the categories and parameters used within each selected calculator is performed following practical utilization. To investigate the calculation approach utilized and transparency (RQ3 and RQ4 respectively), information provided on the websites of the selected calculators or mobile application were analysed. In case such information were not published online, the developers of respective tools were contacted. For answering RQ5, carbon emissions following profile analysis was conducted (Padgett, et al., 2008). For this, five random profiles were created with different transport-related behaviours and then, the carbon emissions for each profile were computed on each selected calculator. Results obtained were then analysed and used to answer RQ5. These profiles were also created for individuals from different countries around the world to target calculators that cater for different countries, rather than focusing on country-specific calculators. These five profiles are detailed as follows:

- ***Profile 1***: John Ross, aged 50, is a full-time lecturer at Middlesex University Mauritius. He is married and lives in the eastern region of Mauritius with his wife and two children. John travels around 70 km every day in his 2004 Honda Civic (IMA Executive 5MT) car and he owns no other vehicles. He takes his family for holiday once a year to travel to London by economy class.
- ***Profile 2***: Emma McAteer is a Marketing Officer at the Middlesex University in UK since 2008. She is married with no children and lives in a 2-bedroom apartment building in Hendon (UK) with her husband. Emma travels to work in her own car, which is a BMW X5 Series E70, and her daily mileage is around 50km. The couple travelled to Australia and Dubai by economy class during the last year.

- ***Profile 3***: Tony Taylor is a laboratory assistant based in Mauritius since 2010. He is single and lives alone in a 2-bedroom house near his place of work. He travels around 50km daily to work on his motorbike (medium 125cc – 500cc). Tony does not travel abroad during his holidays.
- ***Profile 4***: Grace Mason is a marketing consultant in a large private firm in Dubai. She lives alone in a two-bedroom flat in Deira. Grace travels around 40 km every day to work via train. Additionally, she has a Toyota Corolla (auto 1.8) and drives around 120 km per week for shopping and to meet friends. During the past year, she travelled 5 times to different international destinations namely, London, Johannesburg, Paris, New York and Madrid.
- ***Profile 5***: Mike Philipps is a management support officer at Middlesex University (Malta). Mike travels around 35 km every day to his place of work and back home by bus and he owns no other vehicles. He uses public transportation to travel to all places. In the last year, he travelled to Abu Dhabi (economy class) and also went on cruise to Malaga, Paris and London for 10 days in a single trip.

For investigating RQ6, the selected calculators were practically used for a period of three months to study key messages and files sent from the tools within any integrated mailbox on the system or via registered emails during profile creation. Finally, to analyse RQ7 and RQ8, relevant previous research questions were revisited to further analyse collected data and findings.

3.4 Calculator Search

In order to search the calculators to be used for answering the formulated research questions, a query was initially made using Google, Google Play and APKPure for relevant keywords, similar to the calculator search framework used in the study by Kim and Neff (2009). Google was utilized as search engine since it prioritizes results based on highest relevancy as well as employs different techniques in order to enhance search quality via page rank calculation, anchor text, and other important features (Grin & Page, 1998; Lavania, et al., 2013). On the other hand, Android-based applications were targeted as the operating system has been regarded as the most popular one around the world (Network World, 2018). In the initial search, out of the initial 136 calculators identified (including Google, Google Play and APKPure search results), 108 calculators were found to measure the impacts from calculation of water, land-use, GHG footprints and some also required technical knowledge about life-cycle assessment modelling. Furthermore, there were also calculators that were country specific, commercial, involved principally diet-related processes and downstream of product purchase, which were disregarded due to their irrelevance for this study. In addition, the country-specific calculators would not be able to compute the carbon footprint of all the profiles defined in the previous section and were thus not considered. Following the screening process, 15 calculators were identified to directly or indirectly measure personal transport-related carbon emissions. Ultimately, out of the 15 calculators, 10 were selected for this study since these tools were not restricted to a single country. These include 5 web-based and 5 mobile-based personal carbon footprint calculators. These selected calculators are listed in Table 2 along with their respective name and Uniform Resource Locators (URL).

Calculator Name	Platform	Description and Link
Carbon Footprint	Web	This calculator is made available by Carbon Footprint Ltd, a company registered in the UK. This company provides calculator for both individuals and businesses. Link: https://www.carbonfootprint.com/measure.html
Cool Climate	Web	This calculator has been developed by the Cool Climate Network initiated by the University of California, Berkeley, in partnership with the Government, businesses and NGOs in the U.S. Link: https://coolclimate.berkeley.edu/calculator
I2Sea Calculator	Web	This tool is part of the Inquiry to Student Environmental Action (I2SEA) project, which provides curricular tools on environmental related subjects. The project involves the collaboration between different research groups from the University of Washington, Stanford University and University of Gothenburg. Link: https://depts.washington.edu/i2sea/?page=fpcalc#
Carbon Story	Web	This free tool is implemented by CarbonStory, which is a social enterprise that aims at projects to reduce emissions of GHGs. Link: https://www.carbonstory.org/
Carbon Neutral	Web	This web-based tool is part of the CarbonNeutral Protocol, established by the Natural Capital Partners based in Europe, Middle East, Africa and Asia. Link: http://www.carbonneutralcalculator.com/commutecalculator.aspx
Carbon Sins	Mobile	This mobile-based calculator is provided by the Team Maple from Bangalore (India) and has

		been built by students of Army Public School. Link: https://apkpure.com/carbonsins/appinventor.ai_apsblore_technovation.CarbonSins
Lotus Greens Carbon Calculator	Mobile	This free tool has been developed by the Lotus Greens Developers Pvt Ltd and the calculator is made available only on the Android platform. Link: https://apkpure.com/lotus-greens-carbon-calculator/com.guruinfoways.lotusgreen
My carbon footprint	Mobile	This free mobile-based personal carbon footprint calculator is provided by the OrangeGrey team in their endeavour to fight against climate change. Link: https://apkpure.com/my-carbon-footprint/com.advance.carbonfootprint
Count Carbon	Mobile	This tool is based on data made available from the Carbon Trust reports and is a free carbon calculator made available since 2014. Link: https://apkpure.com/count-carbon/net.icountcarbon
Carbon Calc	Mobile	This mobile-based personal carbon footprint calculator has been published by Vervios Consulting Inc. in 2014 and runs on Android phones. Link: https://apkpure.com/carbon-calc/com.vervios.carboncalc

Table 2 – Details of Selected Calculators

4. Results and Discussions

Based on the previously discussed methodology, findings of the study are discussed as follows:

4.1 Scope

The scope-related data showing the key categories adopted by the selected calculators as well as calculation parameters considered for each category are given in Table 3 and are hereby referred in order to answer RQ1 and RQ2. Results showed that none of the web-based calculators were solely focusing on transport-related personal activities but were also catering for other personal emission categories including household energy use, diet and lifestyle, among others. Although this is expected to render calculation process lengthier, end users could get an estimate of their carbon footprint from other emission categories. Among the reviewed calculators, only Carbon Calc focused on transport-related activities, but was however limited to only road transportation.

In terms of categorization of transport-related emission parameters (RQ1), results showed that existing calculators were using no standardized approach for classifying emission related parameters. The minimum number of categories was one from Carbon Calc and the maximum was nine from Carbon Count, where both were mobile applications. As for transport-related categories, the selected calculators classified information into up to four different categories. Among the labels used, it could be noticed that there was no standard naming convention. For instance, whilst some calculators utilized the term travel, others were using terms such as commute or transportation. The distribution of transport-related categories among the selected calculators is given in the chart in Figure 1.

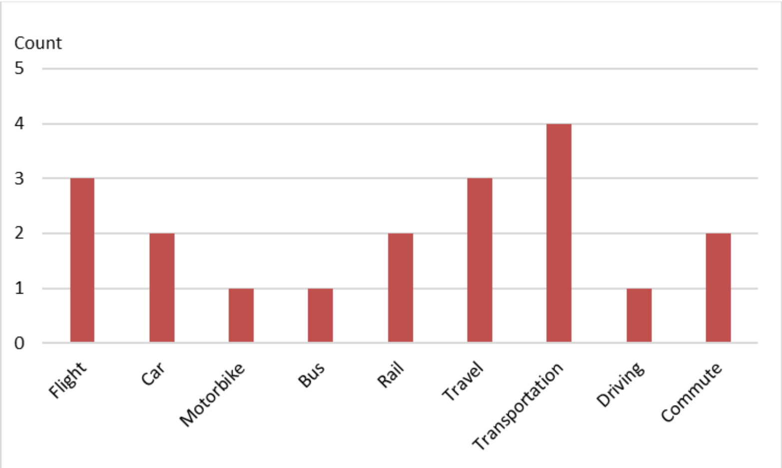

Figure 1 - Distribution of Transport-related categories

Calculator	Key Categories	Parameters Considered for Transportation Modes		
		Road Transport	Air Transport	Rail Transport
Carbon Footprint	• House • Flights • Car • Motorbike • Bus • Rail • Secondary	• Mileage (miles or km) • Vehicle type • Vehicle make • Vehicle model • Year manufactured • Vehicle efficiency • Engine type • Transmission type	• Destination • Class type • Number of trips	• Mileage (miles or km)
Cool Climate	• Travel • Housing • Food • Shopping • Take Action	• Mileage (miles) • Fuel Type (gasoline or diesel) • Vehicle efficiency (miles per gallon)	• Flight distance (short, medium or long haul)	• Mileage (miles)
I2Sea Calculator	• Transportation • Energy and appliances • Food and personal purchase	• Mileage (km) • Vehicle type • Fuel consumption (in litres)	• Number of trips • Hours travelled • Mileage (km)	• Mileage (km)
Carbon Neutral	• Flights • Driving • Home • Commute	• Vehicle type (petrol, diesel, motorcycle, 4x4, sports) • Mileage - annual (km)	• Airport source and destination • Class type • Flight type • Flight distance (short, medium or long haul)	• Mileage (km)
Carbon Story	• Housing • Food • Transportation • Everything else	• Transport type • Mode of travel • Vehicle efficiency • Mileage (miles or km)	• Flight distance (short, medium or long haul) • Number of trips • Mileage (miles or km)	• Vehicle efficiency • Number of trips • Mileage (miles or km)
Carbon Sins	• Household • Travel • Lifestyle	• Fuel consumption (Petrol or Diesel in litres)	• Mileage (km)	• Mileage (km)
Lotus Greens Carbon Calculator	• Domestic energy consumption • Transport • Lifestyle	• Fuel type for private vehicle (Petrol, diesel, CNG or LPG) • Fuel consumption (liters per month or Kgs per month) • Mileage for public transport (km)	• Number of hours travelled	• Number of hours travelled
My carbon footprint	• Flight • Train • Car • House • Living • Others	• Car type • Mileage (miles or km)	• Mileage (miles or km) • Ticket type (one-way or return)	• Mileage (miles or km)
Count Carbon	• Holiday travel • Weekend leisure • House heating • Food & catering • Household appliances • Washing • Clothing and footwear • Commuting • Government uses	• Mileage (miles)	• Destination • Number of trips	• Mileage (miles)
Carbon Calc	• Road transportation	• Mileage (km or miles) • Vehicle efficiency (litres per km) • Number of trips • Fuel type (gasoline or diesel)	None	None

Table 3 – Categories and Calculation Parameters of Calculators

As depicted in Table 3, none of the studied calculators comprehensively considered marine transport as part of the calculation categories. Only Carbon Neutral has ferry as one parameter among the categories. This is an important limitation of existing carbon footprint calculators as individuals could emit an important amount of carbon through marine transportation from cruises, ferries and speedboats, among others (Dickinson & Vladimir, 2007). Besides, My Carbon Footprint mobile-based calculator also catered for cable car transport with mileage as input (both in miles and km), which was a unique feature among the studied calculators. Additionally, in terms of calculation period, 8 out of the 10 reviewed calculators were computing carbon emissions on an annual basis.

Only Carbon Sins and Lotus Greens permitted monthly calculation whilst Carbon Footprint online calculator was the only one allowing computation for a custom date range. The predominance of annual based calculation also implies potentially limited interaction with such tools by end users, who would be calculating personal carbon emissions only once a year.

Similar to categorization of transport-related emission parameters, there is no standard list of variables being considered by the calculators when computing transport-related carbon emissions (RQ2). For road transport, mileage was found as the most common variable sought by the calculators although some required the input in miles whilst others in kilometres. Among the studied calculators, Carbon Footprint was the one considering the largest number of parameters, including vehicle type, make, model, year manufactured, vehicle efficiency, engine type and transmission type, in addition to mileage. This high granularity also highlights that different other calculators are not considering all the necessary parameters in the calculation process, which could impact the accuracy and consistency of computed emissions. On the other hand, calculators including Count Carbon, My Carbon Footprint, Ecological Footprint, Carbon Sins and Cool Climate only considered one or two variables among mileage, car type or fuel type for computation of road transport emissions. Varying granularity also influences user input where high number of parameters could be time consuming and even confusing to the user. However, on the other hand, higher granularity imply consideration of more parameters during the calculation process, thus potentially improving the accuracy of computed carbon emissions. Moreover, most of the calculators did not allow input for multiple cars, thus not catering for people who regularly change cars or use multiple vehicles. Furthermore, analysis of carbon footprint calculators in this study showed that the focus pertaining to the calculation of carbon emissions from road transportation has been on vehicle use phase. However, with enhancements in lower-carbon fuels and in-vehicle technology, a shift in the emissions of a significant amount of carbon towards the vehicle production phase has been reported (Kendall & Price, 2012). As such, the calculators investigated nevertheless do not consider the production and delivery phases of vehicles, which could lead to under-estimated carbon footprints for individuals who often change their vehicles.

For air transport, the calculator considering the biggest number of inputs were Carbon Neutral and Carbon Story, which catered for flight distance (short, medium or long haul), radiative forcing, number of trips and mileage, among others. This also highlights that a limited number of calculators cater for Radiative Forcing (RF), which is a common metric utilized for comparing climate perturbations among aviation scenarios and with total anthropogenic climate change (IPCC, 1999). In addition, varying parameters were noted, thus implying use of different calculation approaches amongst calculators, where for instance, Lotus Greens utilized number of hours for the calculation whereas most involved mileage. Since none of the calculators provided relevant utilities, the conversion process had to be performed on other websites. Moreover, Carbon Footprint and Carbon Neutral were the only calculators to take into consideration class type (e.g. economic and business) in the calculation process. Finally, for rail transport, 8 out of 10 calculators that catered for this category of transport calculated carbon emissions were based on mileage of the trip. Only Lotus Greens Carbon Calculator was utilizing number of hours travelled, thus again showing varying approaches amongst calculators. For this category, the calculator that provided the highest granularity in terms of emission parameters was Carbon Story that sought vehicle efficiency and number of trips, in addition to mileage during the calculation process.

Overall, Carbon Footprint, Carbon Story and Carbon Neutral were the calculators with highest granularity in terms of parameters considered for the different transport-related emission. The varying emission categories and granularity of parameters utilized by the different calculators also shows that there is limited adherence to international assessment standards, thus also potentially influencing the consistency, accuracy and reliability of computed carbon emissions.

4.2 Calculation Approach

During the review of the selected personal carbon footprint calculators, it was found that different calculators were utilizing varying calculation methods or approaches (RQ3). For instance, Carbon Footprint online calculator was making use of the methodology[1] provided by DEFRA for the different emission categories considered (DEFRA, 2012). The calculator also utilizes emission factors provided by different international agencies wherever available notably from the US Department of Energy, Australian Government and the United Nations. Similarly, Carbon Story calculator is based on the updated guidelines and conversion factors provided by DEFRA for the methodology, conversion and emission factors (DEFRA, 2016). However, at the time of this study, Carbon Story was utilising the updated guidelines published in 2016 as compared to Carbon Footprint Calculator which was using the 2012 version. Cool Climate online calculator was inspired from a proposed consumption-based accounting model that is recognized to provide comprehensive assessment of emissions related to individual consumer choices (Wier, et al., 2001; Reinders, et al., 2003; Weber & Matthews, 2008). This approach used by Cool Climate also takes into consideration GHG emissions emitted during the life-cycle of household transportation, among other parameters (Jones & Kammen, 2011). The I2Sea web-based calculator was in turn

[1] CarbonFootprint. Helps and FAQs for the Online Calculators. Available at: http://www.carbonfootprint.com/calculatorfaqs.html

considering the full life-cycle emissions inherent within forms of transportation considered by the tool from cradle to grave, including production, shipment, use and disposal (Hodin, et al., 2016; Berners-Lee, 2011). The calculator derived its emission factors from a variety of sources including US Energy Information Association, UN Climate Neutral Network along with various research articles so as to provide carbon estimates based on key research findings (Hodin, et al., 2016). Similarly, Carbon Story was also principally based on a published research article that proposed 13 normative, evidence-based calculation principles regarding how personal carbon footprints should be calculated (Birnik, 2013). Although comprehensive details are provided on the calculation principles adopted, there is limited information published on methods utilized, in addition to factors considered. As such, whilst some calculators use reporting methodologies provided from governmental institutions such as DEFRA and US Department of Energy, other calculators utilize research-based models and findings for calculating transport-based emissions. A summary is provided in Table 4 depicting the source of the approaches used by the calculators investigated. The remaining calculators however do not provide sufficient information to analyse the underlying calculation approach being utilized. This is further discussed when analysing the transparency of information provided from the reviewed calculators.

Carbon Calculator	Reporting Methodology from Governmental Institutions	Integration of Research based Approaches
Carbon Footprint	✓	×
Cool Climate	×	✓
I2Sea Calculator	✓	✓
Carbon Story	×	✓
Carbon Neutral	✓	×
Carbon Sins	×	×
Lotus Greens Carbon Calculator	×	×
My carbon footprint	×	×
Count Carbon	×	×
Carbon Calc	×	×

Table 4 – Calculation Approach Utilized

4.3 Transparency of Approach

Based on information gathered from the respective websites of the carbon calculators and from email responses obtained, the compiled information related to the transparency of method used, conversions and associated parameters are given in Table 5. At the time of this study, although all calculators mentioned that CO_2 was the GHG considered, there was limited mention whether others including CH_4 and N_20 were considered. In terms of method used, only web-based calculators provided relevant details, thus confirming the lack of transparency on the approaches from mobile-based calculators. Furthermore, information provided pertaining to the calculation method utilized are limited to general approaches (e.g. life-cycle assessment (LCA)) and lack in-depth information on factors considered during the LCA, assumptions made and limitations, among others. Whilst carbon calculators employ a range of emissions factors within their calculation approach, only 4 among the 10 calculators provided the needed details in terms of such factors utilized. As such, absence of these details makes it unclear about whether calculated footprints are relevant to particular regions or if results provided take into consideration up-to-date values from research. Furthermore, details on conversion factors, which relate to the translation of user inputs or behaviours (e.g. using a 2004 Petrol-based car) into the resulting GHG emissions was only provided by a single calculator, namely Carbon Footprint. Likewise, formulae used for calculations were only provided by only one calculator, namely, Cool Climate. This limitation also makes it challenging to reproduce carbon emission results.

As such, similar to related studies, lack of transparency (RQ4) of existing carbon footprint calculators is a major limitation that significantly impacts consistency of results provided (Kim & Neff, 2009; Padgett, et al., 2008; Kenny & Gray, 2009). It was noted that none of the calculators provided full transparency as seen in Table 5. This limitation could be a key barrier for end users and policymakers to properly comprehend the methodologies, variables, and formulae utilized, among other aspects. Lack of transparency can also be an obstacle towards assessment of the accuracy and credibility of results provided by such published calculators.

Carbon Calculator	Published Information				
	GHG being reported (e.g. CO_2, CH_4, N_20 or other GHG)	Method Used	Emission Factors Used	Conversions Factors	Formulae Used
Carbon Footprint	✓	✓	✓	✓	×
Cool Climate	✓	✓	✓	×	✓
I2Sea Calculator	✓	✓	✓	×	×
Carbon Story	✓	✓	×	×	×
Carbon Neutral	✓	✓	✓	✓	×
Carbon Sins	✓	×	×	×	×
Lotus Greens Carbon Calculator	✓	×	×	×	×
My carbon footprint	✓	×	×	×	×

Count Carbon	✓	×	×	×	×
Carbon Calc	✓	×	×	×	×

Table 5 – Transparency of Approach and Parameters Utilized

4.4 Consistency of results

The carbon emissions for the five previously defined profiles were calculated via the selected calculators and respective values are provided in Table 6, in addition to the mean, variance and standard deviation for each profile. For the different profiles, the calculation process was hindered by the fact that different calculators were utilizing different parameters as shown in Table 3 where certain calculators did not cater for some details. For instance, most calculators did not allow input details for car type, year and model in the calculation of the carbon emissions related to road transport. For air transport, different calculators including Carbon Count, Cool Climate and Carbon Sins, did not allow input details such as flight destinations, distance travelled and class type. Moreover, the only calculator which included a car database was Carbon Footprint calculator, which also had the mentioned cars in the different profiles. Furthermore, in many instances, conversions had to be made due to the varying inputs needed by certain calculators, which delayed the calculation process as same calculators did not provide some utilities or tools to be used for the conversions. For instance, Cool climate required miles per gallon, Carbon Sins and Lotus Greens Carbon Calculator required monthly fuel consumption in litres and Lotus Greens Carbon Calculator required flight duration rather than distance. Additionally, there were different cases where the calculation process could not be completed, notably for profiles 3 and 5. Profile 3 principally involves daily use of motorcycle for travelling and calculators including Cool Climate, I2Sea Calculator, Carbon Sins, and Lotus Greens Carbon Calculator do not accommodate for this mode of transport. Similarly, as Carbon Calc does not accommodate for public and foreign travel, and as such, the calculator was not able to calculate carbon emissions for Profile 5.

In terms of collected results, a non-zero value was obtained as variance for all the profiles, thus also indicating dissimilar values in the results. This variance could be due to different factors, namely, varying emission factors being utilized by calculators, calculation method utilized, conversion factors, incorrect assumptions during calculation, among others. As discussed earlier, due to a lack of transparency in the calculation process, it was rather unclear about what the calculators utilize as parameters (e.g. emission factors) and whether the correct values for the country specified for each profile were correctly considered. This is an element of uncertainty that could have a large impact on the variability of results as depicted after the calculation process. In addition, there was only one single instance where two different calculators gave the same carbon footprint results for the same profile, notably, by Carbon Footprint and Carbon Neutral results for Profile 5. Among the five profiles, variance was lowest for Profile 3 and this value could be attributed to the use of a single mode of transport, namely, motorcycle. However, even with a low variance, there were deviations in all the values, and this could be due to conversions needed and varying parameters utilized in the different calculators (e.g. vehicle efficiency in Carbon Story). On the other hand, the biggest variance was noted for Profile 4. This high variance could also be attributed to the involvement of different modes of transport including train, car and flights which had varying parameters for each mode. For this profile, a significant difference of several metric tonnes of CO_2e could be noted as well. As such, it could be seen that the variance in carbon footprint results relates to the number of variables being considered in the calculation process.

To answer RQ5, results showed significant inconsistencies in computed carbon emissions amongst calculators. These inconsistencies were also indicated by variances in carbon footprint results for all profiles. These could be due to the assumptions considered by such calculators as discussed earlier including the model representing the transport system, the different input parameters needed in the calculation process, the detailed algorithm and emission factors used to determine the emission estimates (Linton, et al., 2015; Padgett, et al., 2008). Some of these deviations were of several metric tonnes of CO_2e and similar findings were noted in previous research (Padgett, et al., 2008). Among the studied calculator, it was thus unclear about which one provides the most accurate carbon emissions as values could not be compared against some pre-computed value for each profile, as determining carbon footprint of the profiles was beyond the scope of this paper. In addition, further analysis could be conducted to investigate the carbon footprint for each transportation category of the different profiles analysed. This could provide further information on whether carbon emissions for a particular category of a calculator is in agreement with the same category of other calculators. Furthermore, it was also rare to have two calculators that computed the same carbon emissions for a particular profile. These significant inconsistencies raise important questions on the accuracy and reliability of such calculators. Eventually, such inconsistencies could have an impact on the actions taken or efforts towards reducing personal emissions. Among the calculators, Lotus Greens Carbon Calculator and I2Sea Calculator provided higher estimates of carbon emissions. For both calculators, although the scope is quite similar in terms of categories and calculation parameters, I2Sea Calculator derived its emission factors from different sources and research findings as discussed earlier, which could lead to the high estimates. Overall, only four calculators, namely, Carbon

Footprint, Carbon Story, Carbon Neutral and My Carbon Footprint were able to calculate the carbon footprint of the five profiles and are thus recommended for end-users who utilize different modes of transportation.

Profile	Annual Carbon Emissions ($MtCO_2e$)												
	Carbon Footprint	Cool Climate	I2Sea Calculator	Carbon Story	Carbon Neutral	Carbon Sins	Lotus Greens Carbon Calc.	My carbon footprint	Count Carbon	Carbon Calc.	Mean	Variance	Std. Dev
Profile 1	4.10	10.30	21.69	4.50	3.49	11.12	21.63	4.43	5.05	2.53	8.88	53.29	7.30
Profile 2	6.82	9.50	32.86	7.85	9.85	22.43	48.76	6.07	8.50	4.06	15.67	213.99	14.23
Profile 3	1.69	-	-	1.38	1.56	-	-	0.77	-	-	1.35	0.12	0.35
Profile 4	6.67	23.60	47.02	10.47	7.44	31.93	76.41	7.87	10.32	1.20	22.29	559.49	23.65
Profile 5	0.93	3.40	6.09	1.55	0.93	9.87	2.78	0.75	3.92	-	3.35	9.05	3.00

Table 6 – Analysis of Consistency of Results

4.5 Communication methods

During recent years, there has been varying perceptions on climate change (O'Neill & Hulme, 2009) and climate-friendly actions could be promoted by improving public awareness (Beeharry, et al., 2017; Bekaroo, et al., 2016) since perception is fundamentally linked to awareness (Hartley, et al., 2015; Rees & Pond, 1995). Furthermore, behaviour of people is based on their perception of what the reality is (Dijksterhuis & Van Knippenberg, 1998). As such, proper methods for communicating to a target audience is equally important in order to effectively sensitize people about their adverse contributions towards climate change and at the same time potentially creating an appeal for behavioural change. In this endeavour, carbon footprint calculators have the opportunity to improve awareness on the personal transport-related emission causes, impacts and reduction mechanisms through the provision of relevant information within the tool. However, the comparative analysis performed revealed that among all calculators, only Carbon Footprint online tool provided some limited information on sources & causes of GHG from transport systems. This could be because the reviewed calculators did not focus only on personal transport-related emissions while also including other categories such as household energy use, dietary patterns and lifestyle choices within the calculation process. Such limitation is however important to be addressed by such tools in the endeavour to improve awareness on transport-related emissions. Furthermore, rather than providing information on sources and causes, calculators seem to be more focused on publishing some information on emission reduction mechanisms although both are important. Analysis revealed that 50% of the studied calculators provided information on how to reduce transport-related carbon emissions. However, such information provided also tend to be general information made available through a separate link. None of the studied calculators provided customized emission reduction related information based on carbon emission results obtained by end users following the calculation process or based on previous computed emissions. For instance, if an individual is emitting more carbon when using a motorcycle and zero emissions from use of car, more relevant information on how to reduce emissions from motorcycle use could be provided rather than providing information on car emissions reduction. Transport-based carbon calculators are not providing such feature potentially due to the limited availability of personal transport emissions related averages or baseline information. Moreover, during the process of calculating carbon emissions, limited information is available on how the end-user should proceed for some categories. For instance, limited number of calculators provide details that electricity use and LPG should be taken as the respective amount utilized divided by the number of people within the household. Similar issue arises for personal road travel. For example, if a person travels from London to Newcastle in a private car with four other people, every person would have to take only one fifth of the trip's emissions and limited information is communicated to the end-user regarding such aspects within calculators analysed.

Moreover, as behavioural change is regarded as a gradual process involving consecutive stages (Piotrow, et al., 1997; Prochaska & Velicer, 1997), end users need to be aware of their previous transport-related carbon emissions for effective tracking and behavioural improvement. However, results reveal that only 4 among the 10 calculators have carbon emission tracking features integrated. Moreover, only 2 (Carbon Footprint and Carbon Story) among the 4 calculators allowed end users to save their computed emissions within the system although limited features are available to provide an analysis based on historical trails. On the other hand, the remaining two calculators, namely, I2Sea Calculator and My Carbon Footprint, only allowed users to email calculated emissions rather than storing such details within the system database. Use of such approach by these tools also imply that end users would need to personally analyse emissions periodically and this raises various challenges, namely, loss of details on previous emissions and lack of awareness on effective analysis techniques and lack of motivation, among others.

Among the various mechanisms available to engage and provide end users with updated information on carbon emissions related to personal travelling activities, email seems to be the most commonly used one. This approach is used by Carbon Footprint, I2Sea Calculator, Carbon Story and My Carbon Footprint calculators to send information on computed GHG emissions of end users. Furthermore, besides Carbon Footprint calculator, none of the studied calculators made use of newsletters to regularly communicate updated information to end users. Additionally, live chat and notifications (browser based or heads-up on mobile devices) remain unused by such calculators either to support end users with queries in real time or to remind about key events respectively.

Overall, while communication to end-users remains an imperative way for providing convincing messages about personal transport-related carbon emissions and reduction mechanisms, the comparative analysis revealed that more efforts are needed by such calculators in order to effectively communicate transport-related emissions information and carbon footprint results (RQ6). This is particularly essential so as to further engage end users towards actively utilizing such tools that could eventually help to improve their awareness, perceptions and behaviour (Hartley, et al., 2015; Rees & Pond, 1995; Dijksterhuis & Van Knippenberg, 1998).

Calculator	Info. on sources & causes of GHG from transport systems	Info. on transport-related carbon emissions reduction mechanisms		Allows carbon emission tracking	End-user engagement mechanism			
		Generalized	Customized		Newsletter	Email	Live chat	Notification
Carbon Footprint	✓ (limited info available)	✓	✗	✓	✓	✓ (info on computed GHG Emissions)	✗	✗
Cool Climate	✗	✓	✗	✗	✗	✗	✗	✗
I2Sea Calculator	✗	✗	✗	✓ (email based tracking)	✗	✓ (info on computed GHG Emissions)	✗	✗
Carbon Story	✗	✗	✗	✓	✗	✓ (info on computed GHG Emissions)	✗	✗
Carbon Neutral	✗	✗	✗	✗	✗	✗	✗	✗
Carbon Sins	✗	✓	✗	✗	✗	✗	✗	✗
Lotus Greens Carbon Calculator	✗	✓	✗	✗	✗	✗	✗	✗
My carbon footprint	✗	✓	✗	✓ (email based tracking)	✗	✓ (info on computed GHG Emissions)	✗	✗
Count Carbon	✗	✗	✗	✗	✗	✗	✗	✗
Carbon Calc	✗	✗	✗	✗	✗	✗	✗	✗

Table 7 – Communication Methods

4.6 Platform Analysis

During the comparative analysis, platform-related differences were noted regarding most of the previously analysed aspects in RQ1-RQ6, namely:

- ***Lower granularity in mobile-based calculators***
  As observed in Table 3, the mobile-based carbon calculators exhibited lower granularity as compared to web-based calculators in terms of categories and parameters involved in the calculation process. For the web-based platform, an average of 2 to 3 inputs are required per category whilst mobile-based calculators seek only 1 or 2 inputs per category. This low granularity is potentially due to the various interaction challenges faced when using mobile applications, including small screen size and limited input modalities (Harrison, et al., 2013; Wasserman, 2010)**.**

- ***Lack of transparency in mobile-based calculators***
  The comparative analysis revealed that mobile based calculators exhibit extremely low transparency in terms of calculation methods, emission factors, conversions factors and formulae utilized as part of the calculation process. As shown in Table 5, none of the reviewed mobile-based calculators provided the mentioned transparency-related information within the tool or within any associated website. The limited transparency also made it challenging to analyse the methods being utilized by such calculators and to reproduce results computed by these calculators.

- ***Higher inconsistencies in emissions within mobile-based calculators***

Results in Table 6 show a significantly higher variance and standard deviation between calculators of the mobile platform as compared to the web platform. This also means higher inconsistencies in mobile-based calculators than the web-based ones.

- ***Limited communication from mobile-based calculators***

Even though various innovative communication techniques are available on the mobile platform, existing mobile-based calculators are not effectively utilizing them. As shown in Table 7, none of the mobile-based calculators published information on the sources and causes of GHGs from transport systems. Furthermore, a limited number of calculators of same platform published information on transport-related carbon emissions reduction mechanisms to help improve awareness. Additionally, the same group of calculators made limited use of the end-user engagement mechanisms studied including newsletter, email, live-chat and notifications.

As mobile phone is being regarded as the most widely used electronic device (Tsirulnik, 2017), there is much potential for this platform towards promoting a low-carbon lifestyle (Zapico, et al., 2009). However, the various identified limitations of mobile-based personal carbon footprint calculators could be considered as key barriers to this endeavour.

4.7 General Discussions

By investigating the six comparison criteria through RQ1-RQ7, various shortcomings and issues with personal transportation-based carbon footprint calculators were unveiled. Regarding the scope of such calculators, it was found that although a significant amount of carbon is emitted from personal transportation-related activities, a limited number of such calculator focus directly on transportation. Consequently, different transportation modes (e.g. marine) are overlooked by these calculators and such tools also have varying granularities in terms of parameters used in the calculation process. This varying granularity also highlights a lack of standards governing the development of such tools which developers can consider to ensure that defined standards are met before releasing the calculators for use by end users. Likewise, a missing regulation process also implies that there is no validation performed by regulatory bodies about whether emissions computed by such tools are correct or lie within a defined range. With the lack of regulatory processes, it also makes it questionable about whether carbon calculators providing incorrect emissions should really be online for use by end-users and if not, then who is responsible to prevent such tools from misleading end-users. Furthermore, whilst some calculators utilize guidelines from governmental institutions to formulate their calculation methodology, others are based on research findings or even a combination of both. These varying sources of information could be the main reason for the differing granularities of emission categories and parameters discussed earlier. The worst part was that none of the calculators investigated were fully transparent. The mobile-based calculators studied did not publish any information on how the calculation is performed (e.g. method used, emission factors, conversion factors and formulae). On the other hand, the web-based ones only provided limited information. With the limited information provided by the providers of such solutions, assessing the accuracy and reliability of some carbon calculators by the research community and regulatory bodies is expected to be challenging. Moreover, the computed carbon emissions for the five profiles investigated revealed significant inconsistences between calculators, where deviations were of several metric tonnes of CO2e between some calculators. As such, the reliability of such tools becomes questionable as it is also challenging to determine which tool provides the most accurate results. In addition, whilst it is essential to communicate carbon-related information to end-users to support them towards reducing their carbon footprint, limited communication and end-user engagement mechanisms are integrated by such tools. With limited communication, end users might not feel engaged with such tool and would only use them when needed, particularly once every year. This could be a key reason why a decreasing trend[2] towards searching and using such tools has been noted during recent years. Finally, as the number of active mobile phones has already outnumbered the number of people around the world (Independent, 2014), there is much prospect for such devices to promote low-carbon lifestyle (Zapico, et al., 2009). However, various limitations of mobile-based calculators were revealed, including varying granularities, unclear calculation approaches being utilized, lack of transparency, higher inconsistencies in terms of computed emissions and even limited communication mechanisms implemented. All these shortcomings could hinder the adoption of such tools. As such, with all these limitations within existing transport-related personal carbon footprint, much work remains to be done by different stakeholders given the role of such tools in instructing the general public and suggesting priorities for behavioural change related to personal travel. Recommendations are proposed in the next section on how these issues could be addressed.

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[2] Google Trends on Carbon Calculators:
https://trends.google.com/trends/explore?date=all&q=carbon%20calculator

Besides, this study was also undermined by different limitations. Firstly, limited information was made available by developers of the tool especially for analysing the calculation approach and transparency of the different tools. In addition, as discussed earlier, for answering the formulated research questions, country-specific calculators were not considered. Analysing country-specific calculators could give further information on different aspects investigated while also providing the opportunity to compare carbon footprints estimated by country-specific calculators against those used in this study. However, such investigation was beyond the scope of this paper. Similarly, the calculator search method involved in this study could be expanded to consider calculators on platforms such as App Store (Apple) and Windows Apps (Microsoft Store).

5. ENHANCING TRANSPORT-BASED CARBON CALCULATORS: A TAXONOMY

As discussed in the previous sections, different limitations within existing transport-related personal carbon footprint calculators were identified. To properly organise and recommend potential enhancements that could be made to transport-based carbon calculators (RQ8), a taxonomy is proposed in Figure 2. A taxonomy is a classification system and has been considered as an essential guide during research (Earley, 2011). The proposed taxonomy in Figure 2 consists of three essential building blocks where enhancements on existing transport-based carbon calculators are needed, and these are standardisation, technology and user focus. These are further discussed as follows:

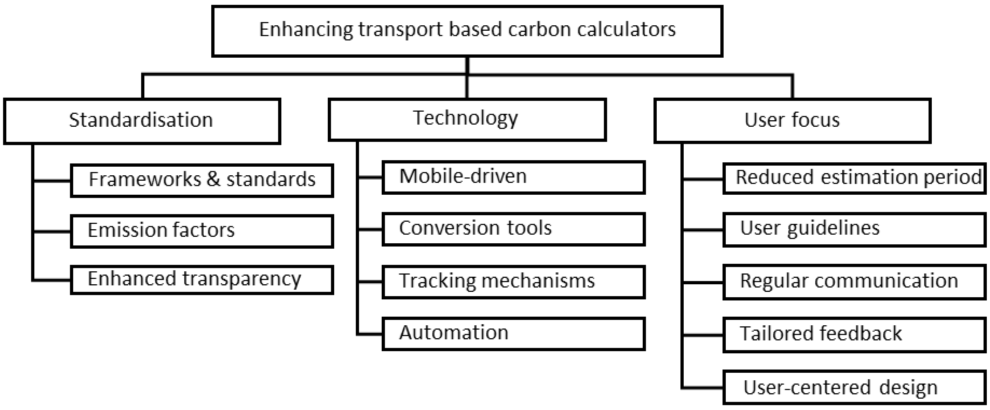

Figure 2 – Proposed Taxonomy for Enhancing Transport-based Carbon Calculators

5.1 Standardisation

The comparative analysis showed that there is no mention about conformance of existing calculators to international regulatory frameworks and standards. This is also because of lack of such frameworks and standards that govern and regulate such tools. As such, there is a need for regulatory organizations and research to delve into the establishment of such frameworks and standards (Robinson, et al., 2018; Bekaroo, et al., 2019). Such standards could regulate the scope, parameters and factors utilized by such calculators. Furthermore, as rules in the form of policies, protocols and legislations are recognized enablers of environmentally sustainable actions (Gillingham, et al., 2009; Greening, et al., 2000; Herring, 2006), their establishment could better ensure that existing calculators conform to defined standards. Once appropriate standards, frameworks and policies are established, regular assessments could be conducted by regulatory bodies on published calculators to ensure conformance to established standards. Implementation of policies, frameworks and standards could be an all-rounder solution to key issues raised in terms of scope, methods used, transparency, consistency of results and communication. Furthermore, same aspects could be part of the assessment process conducted by regulatory bodies. The enhancements related to standardisation needed are further discussed as follows:

- ***Frameworks and Standards***

  Firstly, there is a need for frameworks and standards that define the key components of transport-based carbon calculators. These could cover categorisation of components (e.g. road transport, air transport, etc.) to be addressed by such calculators, the methodology used to estimate emissions from each mode of transport, regulatory mechanisms, among others. Proper categorization is an essential component of the design of personal carbon footprint calculators and the comparative analysis showed that such tools are utilizing different approaches to categorize emission parameters, ranging between one and nine categories. Because of this limitation, some categories only seek one input whilst others showed to require up to eight parameters, thus implying varying granularity. In addition to the varying granularity, different calculators showed incompleteness in terms of parameters considered for specific categories. For instance, some calculators principally considered mileage as input for air travel whilst other important parameters include class type, among other parameters (Miyoshi & Mason, 2009). In addition, emissions from the vehicle production and delivery phases are not considered by existing calculators, as discussed earlier. Similarly, most calculators reviewed did not consider marine transport as part of the calculation process even though there is much focus on reducing GHGs emitted by the shipping industry (Coelho, et al., 2015). Furthermore, a limited number of calculators kept track of the car-sharing or lift-sharing as option along with potential emissions savings, although this is a growing sustainable way of transport. As such, although there is no such rule for equal number of parameters per category, a standardized approach to categorize transport-related categories and parameters could reduce confusion among users. Also, standardized categories, parameters and approaches could improve consistency of results amongst calculators. Moreover, the method used to estimate carbon emissions is unclear for many calculators as discussed earlier and defined standards could recommend particular methods to be used for varying scope and regions. Finally, the establishment of such frameworks and standards could better help to regulate the publishing and use of such calculators. During recent years, there has been an increasing number of such calculators made available on different platforms (e.g. Play Store) and this could be confusing to end users of mobile phones about which calculators to download and utilize. As such, presence of such frameworks and standards could help regulate publishing of transport-based calculators such that if any published tool does not match published standards, actions could be taken by regulatory institutions towards removing access to the calculator to the public.

- ***Emission factors***

As discussed earlier, there are limited insights on the emission factors utilized by many calculators (especially mobile-based ones) that consequently led to a variance in carbon footprint estimations provided by various tools as shown in Table 6. In addition, because of the lack of emission factors for different countries, global averages are utilized, thus reducing the accuracy of estimated carbon footprints. As such, countries which have not yet established emission factors could investigate and publish such values in order to improve accuracy of computed carbon emissions. Calculator designers and developers could then utilize emission factors published by regulatory institutions at the national or international levels.

- ***Enhanced transparency***

Carbon footprint calculators have often been criticized for their lack of transparency (Padgett, et al., 2008) and this barrier makes peer-reviews a difficult process thereby reducing feedback from the community (including experts, researchers, general public). In order to address this issue, such tools should provide clear, accurate, specific and transparent information related to the calculation process including GHG being reported, method used, emission factors utilized, conversions factors involved, and formulae made use of, among others. For this, such information could be complemented on the existing websites of online calculators. For mobile applications, such details could be included as a supplementary feature or publicized online through blogs to improve accessibility to the broader internet users.

5.2 Technology

In the past, due to technological innovations, both online and mobile-based calculators emerged as tools to enable individuals to estimate their carbon emissions. Innovations in technology have the potential to improve transport-based carbon footprint calculators in different ways, discussed as follows.

- ***Mobile driven***

While smartphone has already overtaken the computer and laptop as device to access the internet (Temperton, 2015), there is much potential for this platform towards promoting a low-carbon lifestyle (Zapico, et al., 2009). As such, carbon calculator designers could better capitalize on the potential of the mobile-based platform for accessibility reasons. However, analysis performed in this study revealed that limitations within existing mobile-based calculators outweigh that of the web-based platform. As such, calculator designers should better address each limitation in terms of scope, transparency, consistency and communication using techniques discussed.

- ***Conversion tools***

The reviewed transport-related carbon calculators utilize varying metrics for key parameters needed in the calculation process. For instance, whilst some calculators utilize kilometres for distance, others utilize miles. Likewise, some utilize gallons and others require input in litres. Additionally, certain calculators seek air flight distance in kilometres while for others, the source and destination airports must be input. As such, to simplify ease of use, tools conversion tools could be included in the calculators (e.g. tool to convert distance from miles to kilometres and vice versa, flight distance calculator, etc.).

- ***Tracking mechanisms***

During the study, it was found that a limited number of calculators have carbon emission tracking features integrated. As such, these tools could better allow end-users to save their carbon emissions within the system through an integrated database. By enabling this feature, end-users would be able to keep track of their previous emissions to eventually apply reduction mechanisms. Furthermore, based on historical trails, more customized and intelligent carbon reduction advices could be given to end-users to better assist them in reducing their transport-related emissions. Moreover, this would improve the scope for the development of carbon forecasting algorithms for personal travel-related activities.

- ***Automation***

The comparative analysis showed that none of the calculators investigated attempted to automate some aspects of the data collection or calculation process. Automating some of the aspects could simplify user input while making the calculation process quicker. For instance, using Global Positioning System (GPS) of mobile phones, changes in locations and distance could be captured automatically by the device and it could be used to eventually compute associated emissions.

5.3 User focus

As discussed earlier, transport-based carbon calculators have a key role in instructing the general public about their personal carbon emissions as well as providing insights about how to reduce such emissions in addition to impacts on climate change. The prospects of such calculators to improve knowledge and influence user behaviour can only be realised if such tools are used (Salo, et al., 2019). As such, the design of such calculators should particularly focus on end-users and towards improving user experience. During the comparative analysis, various limitations were found such that different improvements are needed towards better focusing design for end-users. These improvements are further discussed as follows:

- ***Reduced estimated period***

Analysis revealed that eight out of the ten reviewed calculators were calculating carbon emissions on an annual basis and were not catering for monthly or custom period calculation. The use of such tools on an annual basis also implies limited interaction by end users. As such, to promote interaction and engagement, the calculation period could be reduced to a monthly basis similar to Carbon Sins and Lotus Greens. Computing carbon emissions for custom dates could also be implemented as a feature to provide flexibility to end users.

- ***User guidelines***

The analysis conducted revealed that limited information is available on the calculation process such that end-users should only consider their own individual emissions when using shared transportation modes (e.g. car-pooling). To address this issue, calculator designers should provide clearer guidelines for the calculation of different aspects. For instance, for road trips, calculators should clearly mention that personal emissions are obtained by dividing the total mileage by the number of persons within the house. In addition, to better guide the end user, standard values could also be provided as an example for such criteria. These values could be obtained directly from existing research by computing averages based on values input by previous users within any online database being utilized.

- ***Regular communication***

Effective communication and good quality of information are necessary to reduce scepticism in the domain of carbon management and control (Bui & de Villiers, 2017; Penz & Polsa, 2018). Although several innovative communication mechanisms are available, many calculators are not making their effective use. To improve communication and to better engage end users by providing them with up-to-date information on personal carbon related aspects, newsletters, regular emails, live-chat and notifications, among others could be used.

- ***Tailored feedback***

Results showed that only general information on carbon emission reduction mechanisms are made available within the carbon footprint calculators studied. Instead, more effective and tailored feedback could be provided to end-users on how to reduce individual carbon footprint based on established baselines, averages or previous emissions computed by users of such tools. In order to achieve this, Information Technology related concepts including artificial intelligence, data mining and machine learning could be applied.

- ***User-centred design***

Some calculators showed varying ways of presenting information where some are even difficult to read and notice. In order to improve experience of end-users while using the transport-based carbon calculators, designers of such tools could utilize user-centred design (UCD) approaches. The UCD is a framework consisting of different processes in which different aspects such as usability goals, workflow and user characteristics are given thorough attention at every stage of the design process (Garrett, 2010).

6. CONCLUSIONS

This paper investigated how carbon footprint calculators account for emissions from personal transport-related activities through a set of eight research questions. By answering these research questions, two contributions to literature were targeted. Firstly, insights from a comparative analysis of existing calculators are provided based on application of an adapted research framework. Findings reveal that even though many years have elapsed since the first calculator was conceptualised, various limitations still exist. To start with, there are limited number of such tools that independently focus on carbon emissions from personal transport-related activities. Furthermore, such calculators were found to categorise their emission-related parameters in different ways, while also having different granularities in terms of inputs needed. Also, different calculation methods are being utilized and none of the mobile-based calculators investigated as part of the study mentioned about the adopted method. Moreover, limited information is made available by such tools in terms of method, emission factors, conversion factors and formulae utilized, thus reducing the transparency of these calculators. Even though carbon calculators play a vital role in communicating and quantifying carbon emissions to the general public, results showed significant inconsistencies in results provided amongst calculators, thus also raising important questions on their accuracy and reliability. Additionally, more effective communication mechanisms and tools are needed and that although there is much potential for the mobile platform towards promoting a low-carbon lifestyle, various limitations still need to be addressed. Given the various limitations identified during the comparative analysis, a taxonomy of recommendations has been proposed as second contribution towards providing ways for improving transport-based calculators. These recommendations are opportunities for the research community to further improve travel-based carbon calculators to eventually promote utilization and engagement from end users. As future works, user evaluation of the calculators could be considered in order to obtain insightful information on various aspects including usability, user experience, among others, while targeting to improve adoption of such tools.

7. DECLARATION

- **Ethics approval and consent to participate**
  Not applicable
- **Consent for publication**
  Not applicable
- **Availability of data and materials**
  All data generated or analysed during this study are included in this published article.
- **Competing interests**
  The authors declare that they have no competing interests

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- **Authors' contributions**
  GB and DR defined the scope of the research, collected and analysed data in addition to preparing a first draft of the paper. AZ extended the analysis and discussions presented in this paper. DN assisted in defining the taxonomy presented in this paper and provided support in editing and finalising the manuscript. All authors read and approved the final manuscript.

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