PONTIFÍCIA UNIVERSIDADE CATÓLICA
DO RIO DE JANEIRO

Ana Luiza Carvalho Ferrer

Carbon emissions in transportation: A synthesis framework and mobile application

Dissertação de Mestrado

Thesis presented to the Programa de Pós-graduação em Engenharia de Produção of PUC-Rio in partial fulfillment of the requirements for the degree of Mestre em Logística.

Advisor: Prof. Antonio Márcio Tavares Thomé

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Abstract

Ferrer, Ana Luiza Carvalho; Thomé, Antonio Márcio Tavares. **Carbon emissions in transportation: A synthesis framework and mobile application**. Rio de Janeiro, 2021. 74p. Dissertação de Mestrado - Departamento de Engenharia Industrial, Pontifícia Universidade Católica do Rio de Janeiro.

With a worldwide growing concern for greenhouse gas (GHG) emissions and their impact on human health and the environment, transportation becomes a central theme in mitigation, being responsible for 14% of human GHG emissions. In order to build endurance to climate change, transportation services must not only adapt to the current scenario, but also act quickly to avert future changes. Deeply rooted changes in socio-technical systems will be necessary to achieve significant CO_2 reduction and secure the wellbeing of future generations. The objectives of this study are to (1) achieve a comprehensive view of the current state of carbon mitigation in the transportation sector and (2) contribute to the current sustainability scenario by raising awareness among scholars and practitioners. This is done thorough a systematic literature review, engrained in the socio-technical transition theory and in the structural theory of contingency, and through the development of a CO_2 calculator. Twenty-one review papers are selected for full-text examination in the area of carbon emissions in transportation. Enablers, barriers, benefits, disadvantages and metrics in carbon emissions reduction are identified and a comprehensive framework is built. Results provide a view of the current scenario of sustainability in transportation and allow a better understanding of the factors influencing carbon emission initiatives in transportation, as well as its outcomes. A mobile iOS app is developed to estimate CO_2 emissions. The app is available for download at the App Store under the name of “LogCO_2: Carbon Emissions Calculator”. A scenario planning simulation is offered, showing potential uses of the technological product. The software will also be submitted for registration at the Brazilian INPI institute.

Keywords

Sustainability; Socio-technical transitions; Contingency theory; iOS application.

Resumo

Ferrer, Ana Luiza Carvalho; Thomé, Antonio Márcio Tavares. **Emissões de carbono no transporte: Um framework de síntese e aplicativo móvel**. Rio de Janeiro, 2021. 74p. Dissertação de Mestrado - Departamento de Engenharia Industrial, Pontifícia Universidade Católica do Rio de Janeiro.

Com uma crescente preocupação mundial com as emissões de gases de efeito estufa (GEE) e seus impactos na saúde humana e no meio ambiente, o transporte passa a ser um tema central, sendo responsável por 14% das emissões humanas de GEE. A fim de construir resistência às mudanças climáticas, os serviços de transporte devem não só se adaptar ao cenário atual, mas também agir rapidamente para evitar mudanças futuras. Mudanças profundamente enraizadas nos sistemas socio-técnicos serão necessárias para alcançar uma redução significativa de CO_2 e garantir o bem-estar das gerações futuras. Os objetivos deste estudo são (1) alcançar uma visão abrangente do estado atual da mitigação de carbono no setor de transporte e (2) contribuir para o cenário de sustentabilidade atual, aumentando a conscientização entre acadêmicos e profissionais. Isso é feito através de uma revisão sistemática da literatura, com base nas teorias de transições socio-técnicas e contingência, e por meio do desenvolvimento de uma calculadora de CO_2. Vinte e um artigos de revisão são selecionados para leitura de texto completo na área de emissões de carbono em transporte. Habilitadores, barreiras, benefícios, desvantagens e métricas sobre o tópico são identificados e um *framework* é construído. Os resultados fornecem uma visão do cenário atual de sustentabilidade em transportes e permitem um melhor entendimento dos fatores que influenciam a redução de emissões de carbono retratados na literatura existente. Um aplicativo móvel iOS é desenvolvido para estimar as emissões de CO_2. O aplicativo está disponível para download na App Store com o nome de "LogCO2: Calculadora de Emissões de Carbono". Uma simulação de planejamento de cenário é oferecida, mostrando os usos potenciais do produto tecnológico. O software também será submetido a registro no instituto brasileiro do INPI.

Palavras-chave

Sustentabilidade; Transições sócio-técnicas; Teoria da contingência; Aplicativo iOS.

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1
Introduction

Over the last few decades, concerns over climate change have risen steeply due to increased knowledge on its consequences to the environment, economy and humanity. According to the World Health Organization (2018), roughly 4.2 million deaths worldwide are caused by outdoor air pollution every year. Reducing greenhouse gas (GHG) emissions, particularly CO_2, has therefore become a common and inevitable goal to reduce the impacts of climate change.

When touching the theme of GHG emissions and air pollution in general, the topic of transportation becomes inescapable due to the sector being one of the greatest contributors to global warming. According to the Intergovernmental Panel on Climate Change (2014), the transportation sector accounted for 14% of all anthropogenic GHG emissions and 27% of final energy use in 2010. It was also responsible for 49 Gt of CO_2 emissions that year, which are projected to double by 2050 (Intergovernmental Panel on Climate Change, 2014).

Transportation includes road, rail, air and sea and may refer to the transportation of passengers as well as freight. While it is common to focus on the emissions produced by exhaust gases during transportation operations, transportation generates environmental impacts at every step of its life cycle, including infrastructure construction and maintenance; vehicle, airplane and ship manufacturing, maintenance and disposal; and operation (Chapman, 2017).

One can also argue that at the same time transportation is affecting climate change, climate change is in turn also affecting transportation. Transportation is, in general, highly susceptible to weather conditions; and, while transportation systems and infrastructure are built to endure local weather conditions, continuous climate change is creating vulnerabilities in such systems (Eisenack, 2011).

In order to build endurance to climate change, transportation services must not only adapt to the current scenario, but also act quickly to avert future changes. Individual carbon mitigation measures can only reduce emissions so far; deeply rooted changes in socio-technical systems will be necessary to achieve 80% reduction in carbon emissions (Geels, 2012). Drawing on socio-technical transitions theory, a multi-disciplinary and holistic approach is needed to fully understand climate change, its impacts, and how to abate it (Schwanen *et al.*, 2011; Geels, 2012). On a review of sustainable urban infrastructure, Ferrer *et al.* (2018) highlight the existing interplay between economy, society and technology in solving urban infrastructure issues. Besides, there is a lack of applied and easy-to-use tools for achieving carbon emission reduction estimates.

With the goal of achieving a comprehensive view of the current state of carbon mitigation in the transportation sector, the following research questions are put forward:

> RQ1 - What are the main barriers, enablers, benefits and disadvantages of carbon emission reduction in transportation?
>
> RQ2 – What are the main dimensions or categories utilized to describe the initiatives for carbon mitigation in the transportation sector?

In answering these RQs, this dissertation's general objective is to contribute to the transition to a lower carbon society through a better understanding of the dimensions, enablers, barriers, benefits and disadvantages of existing measures for the reduction of carbon emission.

To attain this general objective, this study will (i) review the extant literature with the backdrop of multi-level sustainability transition theory and contingency theory to offer an analytical synthesis framework, and (ii) propose a technological product as an iOS mobile application geared at scenario simulations to estimate CO_2 emissions from transportation. A tertiary review of carbon emission mitigation strategies in transportation is performed. This type of systematic literature review was chosen because it provides a comprehensive and reproducible synthesis of research to date on the topic. The CO_2 emissions calculator mobile iOS app was developed with the goal of making environmental impact a more accessible and approachable metric for both transportation and chemical companies. The calculator is offered as a technological product that can facilitate practitioners and academics' awareness and is a demonstration tool for the carbon emission effects of different transportation modes and fuel types. It is expected that the fulfilment of the objectives should contribute to the theory and practice of carbon emissions strategies in the transportation sector.

The study is organized as follows: Chapter 1 is this Introduction. Chapter 2 provides a theoretical background on socio-technical transitions and contingency theories subjacent to the analysis of the carbon emission strategies in the transportation sector. Chapter 3 describes the methodology adopted for the study. Chapter 4 presents results from the tertiary research and the CO_2 emissions calculator. Chapter 5 concludes the study with discussions of findings, deriving practical implications and directions for future research.

2
Theoretical background

The theoretical background provides the basis for the analysis of carbon emissions in this dissertation. Systematic literature reviews are powerful tools to elaborate and improve existing theories (Seuring *et al.*, 2020). According to Meredith (1993, p. 7) a theory is "a coherent group of interrelated concepts and propositions used as principles of explanation and understanding," and has to satisfy all of Dubin's five requirements. The requirements are: (i) allow prediction and understanding; (ii) being interesting; (iii) being non-trivial; (iv) not including undefined variables; and (v) including boundary criteria.

SLRs are scientific endeavors by their own merits and provide a reproducible and traceable synthesis of what is known about a given research subject (Thomé et al., 2016). This descriptive role of SLRs is paramount for policy elaboration and evaluation but they usually do not address the questions of *how*, *why* and *when* phenomena occur, which rests in the realm of theories (Bacharach, 1989). According to Seuring *et al.* (2020), due to the relevance of theories to operations management and supply chain management (OMSCM) research it is surprising that most SLRs lack a clearly stated theoretical basis. Theory is important to: (i) guide researchers towards relevant topics; (ii) enlighten practitioners; (iii) make sense of empirically generated data; (iv) avoid empiricism or mere "data-dredging" from research, and (v) differentiate science from common sense (Amundson, 1998; Walker *et al.*, 2015). Theory should also guide the prediction of outcomes and the description and explanation of a process or sequence of events, providing a linguistic tool to organize the complexity of the empirical world, and serving as an educational tool about concepts (Colquitt & Zapata-Phelan, 2007).

The use of theories in this literature review follows the guidelines provided by Seuring *et al.* (2020) for the supply chain management field, and apply it to the analysis of carbon emissions in the transportation sector. According to Seuring *et al.* (2020), SLRs can contribute to (i) theory building, mainly through inductive reasoning; (ii) theory modification through abductive reasoning; (iii) theory refinement through deductive logic; and (iv) theory extension, which “borrows theory from outside the field, thereby enriching the studied content and broadening the available theoretical repository” (Seuring *et al.*, 2020, p. 5). This dissertation spouses the fourth view of the role of theories in SLRs.

2.1
Multi-level theory of socio-technical transitions

Significant reductions in carbon emissions can only be achieved through fundamental changes in transportation systems, or socio-technical transitions (Geels, 2012). Socio-technical transitions are characterized as major shifts in socio-technical systems, which may include a variety of interacting components such as “technology, policy, markets, consumer practices, infrastructure, cultural meaning and scientific knowledge” (Geels, 2012, p. 471). They may take decades to gradually develop and are seen as co-evolutionary processes (Geels, 2012).

The majority of transportation research on climate change mitigation to date focuses on technological, economic and infrastructural elements — that is, the ‘technical' side of socio-technical systems (Schwanen *et al.*, 2011). Socio-technical systems, however, are composed of multiple dimensions that are in constant interplay with each other, suggesting there is much to gain from exploring the ‘social' side as well (Schwanen *et al.*, 2011).

Having this in mind, the multi-level perspective (MLP) approach to socio-technical transitions seeks to provide a holistic understanding of elements and actors involved in transportation systems, as well as their interactions (Geels, 2012). It addresses the dynamics between stability and change and how new systems need to surmount a series of challenges in order to overcome the existing regime and establish a new normal (Geels, 2012).

Generally, three main levels are explored in the MLP (Geels, 2012):

- *Niches*, small protected spaces where innovation takes place;
- *Socio-technical regimes*, the place of established practices, technologies and regulations; and

- *Socio-technical landscape,* the wider external context.

Figure 1 illustrates the dynamics involved between the three levels of MLP. Changes and new ideas start in niches; typically emerging from experiments or innovation projects (Geels, 2012). Continuous learning from niches challenge the regime, proposing a transformation or replacement of the existing regime, but are mostly met with barriers formed by lock-in mechanisms (Geels, 2012; Klitkou *et al.*, 2015).

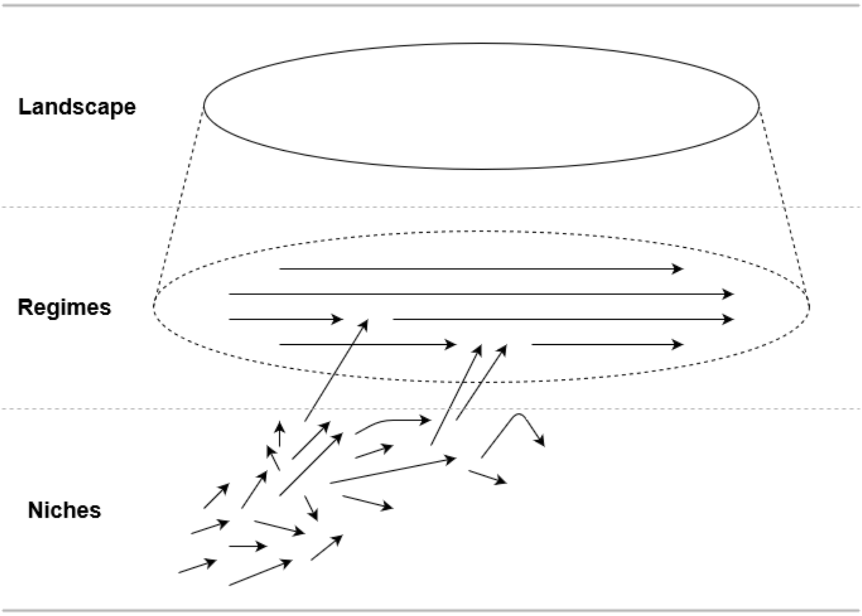


Figure 1 - Levels of multi-level perspective

Source: Adapted from Geels, 2012.

Other influential analytical frameworks in high-level sustainability transition research are the Technological Innovation System approach (TIS), the Strategic Niche Management (NMS), and the Transition Management (TM) (Köhler *et al.*, 2019). Table 1 provides a summary of the theoretical basis and main constructs of each analytical framework.

These analytical frameworks bring a high-level perspective to the analysis but they might lack the fine-grained details needed to understand the *how*, *why* and *when* of specific carbon emission reduction initiatives and its outcomes in the society and the environment. The contingency view in operation management research can complement the MLT approach to socio-technical transition in important ways and is briefly summarized next.

Table 1 – Frameworks for sustainability transitions (Adapted from Köhler *et al.*, 2019, p. 4-5)

Analytical frameworks	**Theoretical basis**	**Main constructs**	**References**
Multi-Level Perspective (MLP)	Evolutionary economics, sociology of innovations and institutional theory	Transitions consist of three levels: (i) niches where innovations take place, (ii) established socio-technical regimes where lock-in mechanisms are present, and (iii) wider exogenous landscapes.	Rip & Kemp, 1998; Geels, 2002; Smith *et al*., 2010
Technological Innovation System approach (TIS)	Innovation systems theory and industrial economics	Technological innovations are made up of technologies, actors and institutions. Transitions take place through the following phases: knowledge, experimentation, directed search, market formation, legitimation, resource mobilization, and positive externalities.	Carlsson & Stankiewicz, 1991; Malerba, 2002; Hekkert *et al*., 2007; Bergek *et al*., 2008; Negro *et al*., 2008; Markard *et al*., 2015; Weber & Truffer, 2017
Strategic Niche Management (SNM)	Sociology of innovations and evolutionary economics	Radical innovation is born in safe 'niche spaces' and evolve through learning processes, interactions, social networks, visions and expectations. Quality, expectations, social networks, first- and second-order learning influence determine innovation trajectories created by recursive projects.	Rip & Kemp, 1998; Geels & Raven, 2006; Schot & Geels, 2008
Transition Management (TM)	Complexity Sciences and Government studies	Policy framework composed of four steps: transition arena (strategies); tactical (agendas and plans); operational (on-the-ground experiments, demonstration, implementation); reflexion (evaluation and monitoring).	Rotmans *et al*., 2001; Loorbach, 2010

2.2
Basic elements of the theory of contingency in operations management research

The structural contingency theory of organizations posits that organizations perform well when there is a fit or adequacy between the environment in which it operates, and the structural aspects of the organization. There is a misfit when environment and structure do not match. Organizations perform better when there is fit and perform poorly when there is a misfit between environment and structure (Donaldson, 2001). Figure 2 provides a simple illustration of the expected relationships between the environment, carbon emission initiatives and their outcomes, under the perspective of the contingency theory.

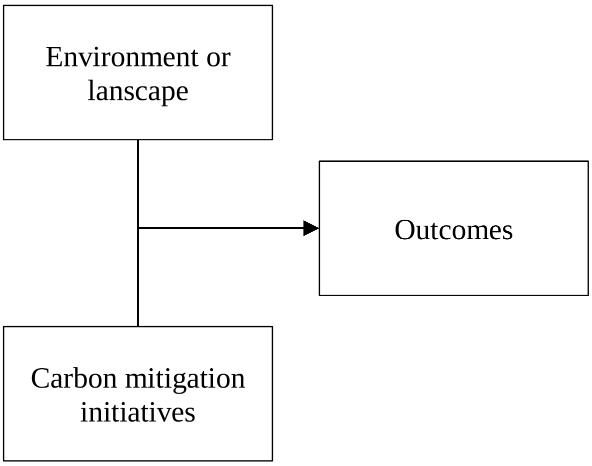


Figure 2 – Effects of the operating environment (landscapes) and carbon emission mitigation on outcomes

The four basic postulates of contingency theory (Donaldson, 2001), extended to the field of transportation carbon emissions, can be expressed as: (i) there is a mutually reinforcing effect between the landscape and the carbon emissions mitigation initiatives; (ii) high landscape-carbon emission fit causes effectiveness and low fit causes ineffectiveness; (iii) there is no universal type of carbon emission initiatives valid for all types of transportation modes and landscapes; (iv) the outcomes of carbon emissions mitigation strategies (its advantages and benefits) are measurable.

Applying the definition of operations management practice contingency research – OM-PCR (Sousa & Voss, 2008) to carbon emissions brings a powerful lens for the theoretical extension of the SLR research. According to Drazin & Van de Ven

(1985), the analysis of environment-structure fit can be done in three different ways, using the logics of selection, interaction or systems. This distinction is important because it provides the elements needed to understand the variables included in current research in carbon emissions in transportation. Under the selection approach the fit between the environment (or landscape) and the structure (here the emissions mitigation initiatives) are assumed to produce the best results in terms of outcomes. Therefore, under this perspective, the response variable (the outcomes) is not formally stated nor measured and the environment-structure fit and its effect on the outcomes are taken as a given. Under the interaction perspective, individual relationships between environment and structural variables produce specific results in terms of outcomes and they are measured individually, variable by variable. Under the systems approach, several environment and structural variables interact internally and among them and their effect on outcomes are jointly analyzed, taking into consideration individual and interaction effects in a systemic way (see Sousa & Voss, 2008, pp. 706-707 for a complete discussion of the typology).

The combination of the MLT approach to socio-technical transition with the OM-PCR provide the theoretical lenses through which the SLR is undertaken. The high-level MLT framework is an overarching analytical framework for transition research and provides a broad frame of reference to analyze carbon emission mitigation strategies and its constituent elements. Its lenses will be paramount to search for a typology of carbon emissions research described in Chapter 4. The OM-PCR lenses will direct the attention to the measurement of the landscape, the carbon emission mitigation initiatives, its outcomes, and the relationships among them, directing the attention to the synthesis framework proposed in Subsection 4.6.

3

Methodology

This chapter describes the methodology adopted to perform the systematic literature review (SLR), including basic statistics from the review and methods applied in the tertiary research, and main formulas and assumptions used to develop the CO_2 calculator mobile application.

3.1
Step-by-step approach for the systematic literature review

There are several types of literature reviews, described by Grant & Booth (2009). The ones identified in this review are *systematic review*, *literature review*, *critical review*, *meta-analysis* and *state-of-the-art review*. S*ystematic reviews* methodically follow a clearly defined procedure to conduct the research. *Literature review*, on the other hand, is a broader term that can describe reviews with a wide range of subject areas, depth and completeness. *Critical reviews* go beyond a sheer description on findings and include a critical assessment of the literature. *Meta-analyses* use statistics to review quantitative studies. Finally, *state-of-the-art reviews* focus on contemporary themes and often provide next steps or directions for future research.

For the tertiary research, the step-by-step approach devised by Thomé *et al.* (2016) and based on Cooper (2010) for systematic literature reviews was adopted. It consists of eight main steps: (i) planning and formulating the problem, (ii) searching the literature, (iii) data gathering, (iv) quality evaluation, (v) data analysis and synthesis, (vi) interpretation, (vii) presenting results, and (viii) updating the review.

For the first step, *planning and formulating the problem*, the theme of carbon emissions in transportation was identified. An initial review team was formed, comprising the author and the dissertation advisor. The topic and its gaps were extensively discussed and debated, resulting in the formulation of the research questions defined in the introduction.

The next step, *searching the literature*, involved selecting scientific databases, defining search keywords and queries, and defining exclusion criteria. Scopus (www.scopus.com) and Web of Science (WoS) (www.webofknowledge.com) databases were selected due to their extensive journal collection and relevance in the scientific community (HLWIKI Canada, 2015; Mongeon & Paul-Hus, 2016).

Table 2 describes the keywords and restrictions used to search the databases. First, keywords related to the topic area, carbon emissions in transportation, were applied. Next, results were filtered based on document type (only articles, articles in press and reviews) and language (English language only). This search yielded 10,423 papers from Scopus and 8,473 papers from WoS, which provided a combined total of 14,137 papers in the topic area after duplicate papers were removed.

For the tertiary research, an additional set of keywords targeting different definitions of literature review proposed by Verner *et al.* (2014) and Thomé *et al.* (2016) was applied to further filter results. This retrieved 236 papers from Scopus and 170 papers from WoS. After duplicate papers were excluded, 333 papers were selected for abstract review.

Table 2 - Selected keywords and restrictions for selecting papers for SLR

Search keywords and restrictions	**No. of papers included**	
	Scopus	**WoS**
("transport*" OR "ship*") AND ("metric*" OR "measur*" OR "quanti*") AND ("green" OR "sustainab*" OR "environment*") AND ("climate change" OR "carbon" OR "CO2" OR "greenhouse effect")	13,322	9,425
Restricted to articles and reviews	10,820	8,559
English language only	10,446	8,473
Total selected from topic area:		18,919
Total selected from topic area (w/o duplicates):		14,159
("research synthesis" OR "systematic review" OR "evidence synthesis" OR "research review" OR "literature review" OR "meta-analysis" OR "meta-synthesis" OR "mixed-method synthesis" OR "narrative reviews" OR "realist synthesis" OR "meta-ethnography" OR "state-of-the-art" OR "rapid review" OR "critical review" OR "expert review" OR "conceptual review" OR "review of studies" OR "structured review" OR "systematic literature review" OR "literature analysis" OR "in-depth-survey" OR "literature survey" OR "analysis of research" OR "empirical body of knowledge" OR "overview of existing research" OR "body of published knowledge" OR "review of literature")	236	170
Total selected for tertiary research:		406
Total selected for tertiary research (w/o duplicates):		303

For the third and fourth steps, *data gathering* and *quality evaluation*, a careful selection of articles was carried out following the PRISMA statement (Page *et al.*, 2021).

The selection of studies for the tertiary review was performed by the authors using PRISMA — Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Page *et al.*, 2021). Figure 3 presents a flow diagram of studies selected and excluded at each level of this process.

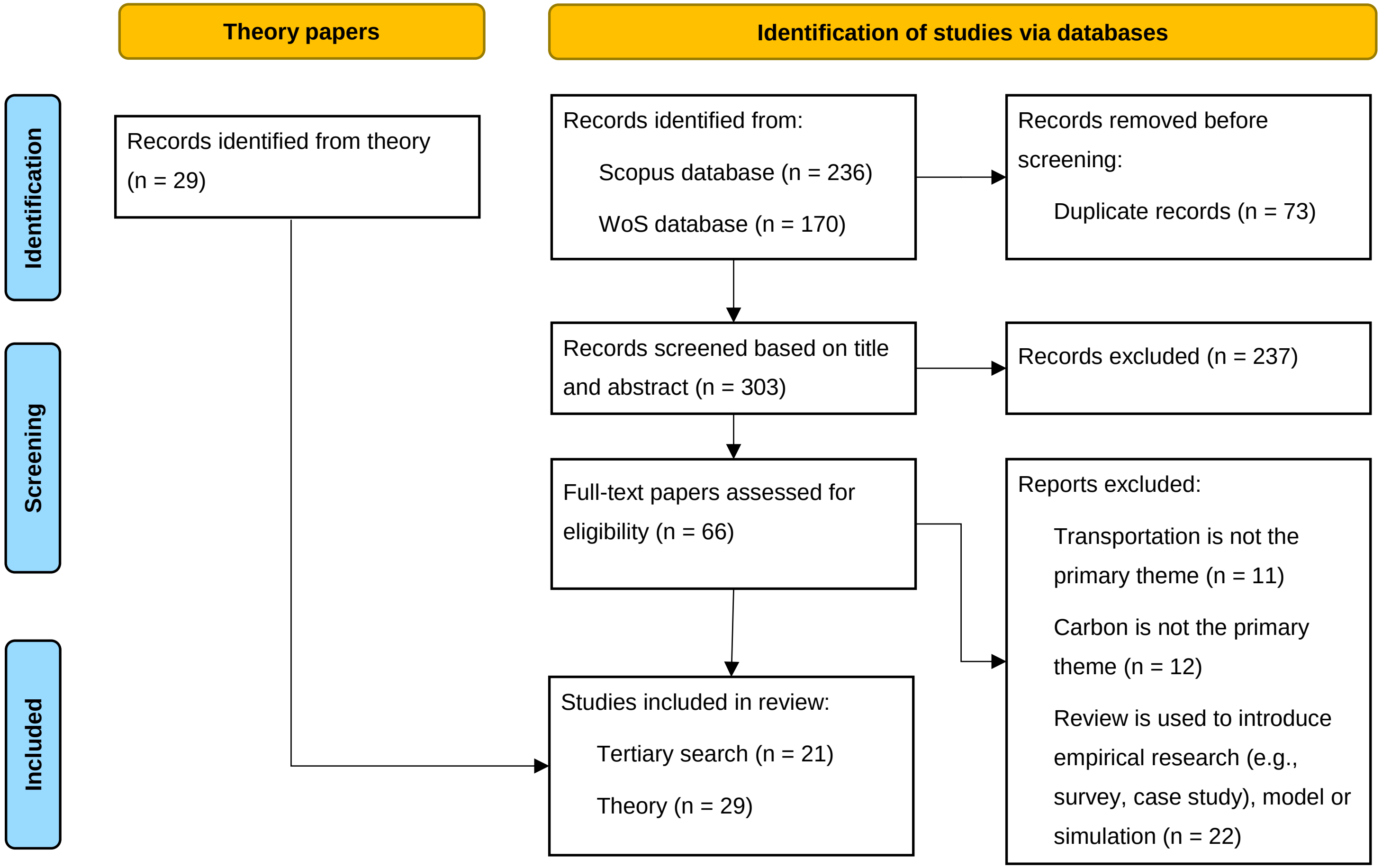


Figure 3 – Flow diagram of studies selected for tertiary research, based on PRISMA (Page *et al.*, 2021)

The database search described in Table 2 yielded 236 studies from Scopus and 170 studies from WoS, of which 73 duplicate records were identified and removed. 303 documents were then selected for screening based on title and abstract. The author and one other reviewer screened articles individually. After an initial round of screening, 83.2% agreement was reached (Cohen’s Kappa = 0.348; Krippendorff’s Alpha = 0.342). Fifty-one cases of disagreement were then debated until consensus was reached between the author and the other reviewer, reaching 100% agreement. 237 records were excluded after screening, leaving 66 papers for full-text review.

During full-text review, the following exclusion criteria were applied: (i) transportation is not the primary theme; (ii) carbon is not the primary theme; (iii) review is used to introduce empirical research (e.g., survey, case study), model or simulation. The third exclusion criteria follows Cooper & Hedges' (2009) definition of research synthesis, which excludes narrowly focused reviews intended to introduce or produce new facts and findings. 55 papers were excluded during this stage, yielding a final 21 papers for the tertiary research.

Chapter 4 and Chapter *5* of this study compose the fifth and sixth steps in the SLR methodology, *data analysis and synthesis* and *interpretation.* These steps were conducted qualitatively using an inductive approach (Seuring & Gold, 2012) and complemented with quantitative co-citation and co-word analyses.

The seventh step, *presenting results*, can be attributed to the study itself and its ensuing publication and distribution. The eighth and final SLR step, *updating the review*, is left as a suggestion for future research and lies beyond the study’s scope.

3.2
Mobile application

For the CO_2 calculator, a mobile application for iOS was developed. The application was developed in Swift programming language using Xcode development environment. CO_2 emissions can be calculated using two different approaches proposed by the European Chemical Industry Council and the European Chemical Transport Association (ECTA & CEFIC, 2011) in "Guidelines for Measuring and Managing CO_2 Emission from Freight Transport Operations”; they are an activity-based approach and an energy-based approach. Equation 1 is used in the activity-based approach and calculates emissions in tonnes of CO_2 as a product of volume, distance and a CO_2 emissions factor. While the user can determine the emissions factor, the application suggests an emission factor based on the selected transport mode according to Table 3.

Equation 1 – CO_2 emissions formula using activity-based approach (Source: ECTA & CEFIC, 2011)

$$\begin{aligned} &CO_2\ emissions \\ &= Transport\ volume\ by\ transport\ mode \\ &\times\ Average\ transport\ distance\ by\ transport\ mode \\ &\times Average\ CO_2\ emission\ factor\ per\ tonne\ km\ by\ transport\ mode \end{aligned}$$

$[Tonnes\ CO_2\ emissions = tonnes\ \times km\ \times g\ CO_2\ per\ tonne\ km\ /$ 1,000,000]

Table 3 - Average emission factors by transport mode (Source: ECTA & CEFIC, 2011)

Transport mode	**gCO2/tonne-km**
Road transport	62
Rail transport	22
Barge transport	31
Short sea	16
Intermodal road/rail	26
Intermodal road/barge	34
Intermodal road/short sea	21
Pipelines	5
Deep-sea container	8
Deep-sea tanker	5
Airfreight	602

For the energy-based approach, Equation 2 was used to calculate emissions, using the product fuel consumption and a CO_2 emissions factor. Same as for the activity-based approach, the user can determine the emissions factor or use a factor suggested by the application and based on fuel type (Table 4). Swift code for the application can be found in Appendices 1-3.

Equation 2 - CO_2 emissions formula using energy-based approach (Source: ECTA & CEFIC, 2011)

$$CO_2\ emissions = Fuel\ consumption\ \times Fuel\ emission\ conversion\ factor$$

$$[Tonnes\ CO_2\ emissions = liters\ \times kg\ CO_2\ per\ liter\ fuel\ /\ 1{,}000]$$

Table 4 - Well-to-wheel fuel emission conversion factors by fuel type (Source: ECTA & CEFIC, 2011)

Fuel type	kg CO_2/liter	kg CO_2/kg
Motor Gasoline	2.8	
Diesel Oil	2.9	
Gas Oil	2.9	
Liquefied Petroleum Gas (LPG)	1.9	
Compressed Natural Gas (CNG)		3.3
Jet Kerosene		3.5
Residual Fuel Oil		3.5
Biogasoline	1.8	
Biodiesel	1.9	

4
Results

This results section presents an overview of the reviews selected for the tertiary research, followed by a typology of carbon emissions reduction in transportation and a framework that summarizes the main findings from the studies. An iOS mobile application for CO_2 emissions calculation in transportation is also presented as a technological product.

4.1
Overview of studies selected for tertiary review

The 21 literature reviews selected for the tertiary research are in Table 5, along with the number of studies reviewed and review methodology. Table 5 also includes the transportation sector each literature review focuses on and sustainability dimensions addressed.

Table 5 - Selected literature reviews with their respective number of studies, review methodology, transportation sector and sustainability dimension

Literature reviews	**No. of studies**	**Review methodology**	**Transportation modes**	**Sustainability dimensions**
Smit *et al.* (2010)	50	Meta-analysis	Road	Environmental ***
Eijgelaar (2011) **	80	Literature review	Air - Tourism	Environmental ***
Li (2011) **	98	Critical review of literature	Multimodal - Urban	Environmental, social and financial ***
Miola & Ciuffo (2011) **	49	Meta-analysis	Maritime	Environmental and social ***
Hawkins *et al.* (2012)	51	Literature review	Multimodal - Hybrid and electric vehicles	Environmental ***
Franco *et al.* (2013) **	190	Literature review	Road	Environmental ***

Literature reviews	**No. of studies**	**Review methodology**	**Transportation modes**	**Sustainability dimensions**
Faris *et al.* (2014) **	80	State-of-the-art review	Road - Intelligent Systems	Environmental ***
Kwan & Hashim (2016)	9	Systematic review	Multimodal - Mass public	Environmental and social ***
Bouman *et al.* (2017)	150	Systematic review	Maritime	Environmental ***
Garcia & Freire (2017)	69	Critical review	Road - Light-duty fleet vehicles	Environmental
Herold & Lee (2017)	66	Systematic literature review	Multimodal - Logistics and freight	Environmental
Czepkiewicz *et al.* (2018)	27	Systematic review	Multimodal - Long-distance leisure travel	Environmental ***
Requia *et al.* (2018)	65	Systematic review	Road - Electric mobility	Environmental and social
Salvucci *et al.* (2019)	8	Critical review	Multimodal - European Nordic countries	Environmental ***
Arioli *et al.* (2020)	40	Systematic review	Multimodal - Urban	Environmental ***
Lagouvardou *et al.* (2020) **	78	Literature review	Maritime	Environmental
Meyer (2020) *	715	Systematic quantitative review	Road freight	Environmental
O'Mahony (2020) **	33	State-of-the-art review	Unspecified - Carbon taxes	Environmental and economic
Oguntona (2020)	11	Narrative review	Air	Environmental ***
Pilz *et al.* (2020)	18	Systematic review of literature	Multimodal - Transport in manufacturing industry	Environmental
Hu & Creutzig (2021)	687	Systematic review	Multimodal - Shared mobility	Environmental, social and financial

* Bibliometric review.
** Total number of references as the exact number of studies reviewed was not stated.
*** Sustainability dimensions inferred by the authors.

The 21 selected reviews in Table 5, combined, reviewed 2,574 studies. These is an approximate number since, as indicated in Table 5, not all studies shared the exact number of studies reviewed. In these cases, the total number of references was inferred as the number of studies reviewed.

Figure 4 illustrates the number of studies selected for the tertiary review by publication date. The reviews spanned 12 years of research in carbon emissions in transportation (i.e., from 2010 to 2021) and out of the 21 selected reviews, six were published in 2020, showing the growing relevance of the subject area.

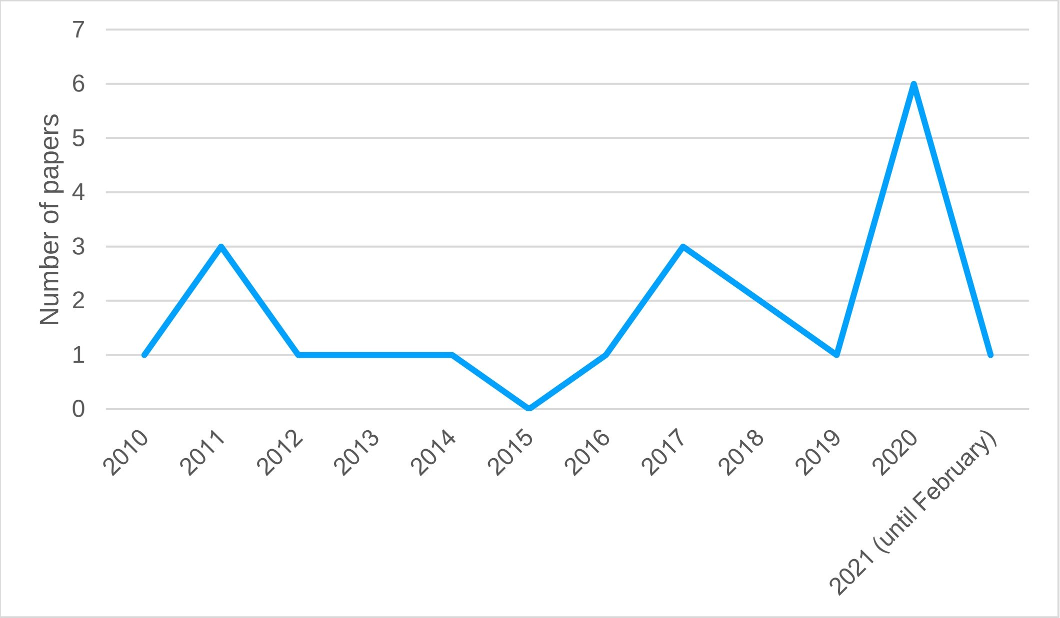


Figure 4 – Number of studies selected for the tertiary review by publication date

The review methodologies observed in Table 5 reflect the nomenclature each author chose to characterize their own study. For a better understanding of the different methodologies adopted in the reviews, however, each study method was grouped into one of the following review types identified by Grant & Booth (2009) in Figure 4 and defined in Chapter 3 – Methodology.

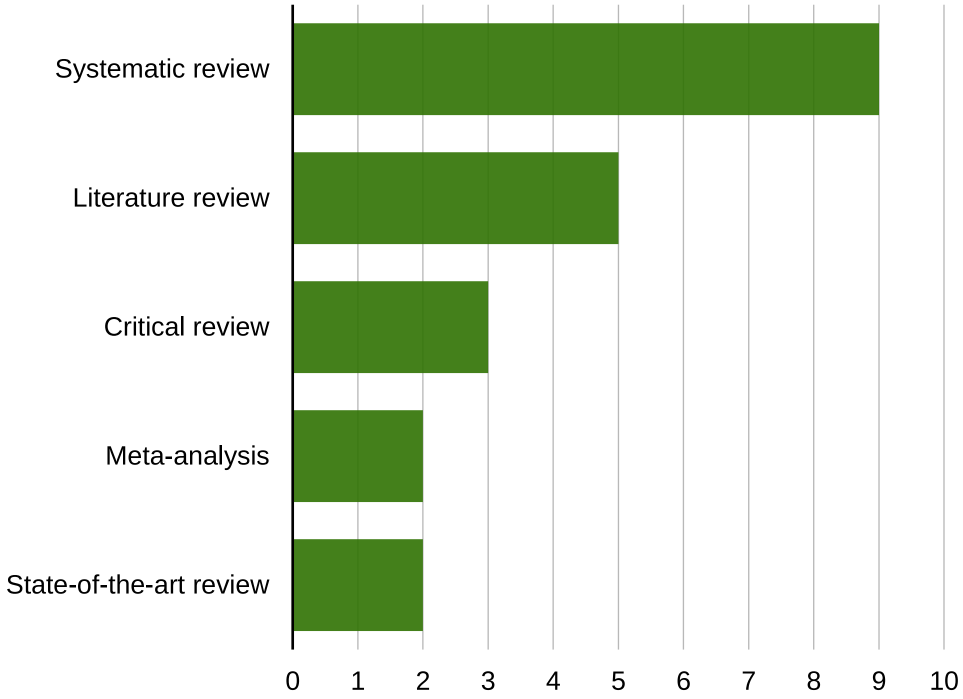


Figure 5 - Methodology adopted in reviews selected for tertiary research

As illustrated in Figure 5, the systematic literature review was the most common methodology adopted (Kwan & Hasim, 2016; Bouman *et al.*, 2017; Herold & Lee, 2016; Czepkiewicz *et al.*, 2018; Requia *et al.*, 2018; Arioli *et al.*, 2020; Meyer, 2020; Pilz *et al.*, 2020; Hu & Creutzig, 2021), followed by narrative literature reviews (Eijgelaar, 2011; Hawkins *et al.*, 2012; Franco *et al.*, 2013; Lagouvardou *et al.*, 2020); critical reviews (Li, 2011; Garcia & Freire, 2017; Salvucci *et al.*, 2019), and, finally, meta-analyses (Smit *et al.*, 2010; Miola & Ciuffo, 2011) and state-of-the-art reviews (Faris *et al.*, 2014; O'Mahony, 2020). Interestingly, even though systematic review is the most popular review approach, all systematic reviews were concentrated in the last six years (*i.e.*, 2016 to 2021), showing an increasing trend towards more rigor in the academic review of the subject.

Regarding transportation mode, studies were classified according to their object of study into road, rail, air, water, multimodal or unspecified in Figure 6. Multimodal refers to a study addressing more than one transport mode (*e.g.*, road and rail when exploring urban mobility) and unspecified refers to a study not specifying the mode of transportation. As expected, road was the predominant transportation mode examined, with eight studies focusing on this mode. Although rail was explored briefly in some studies, particularly those pertaining to urban mobility, none of the studies focused solely on this mode of transportation.

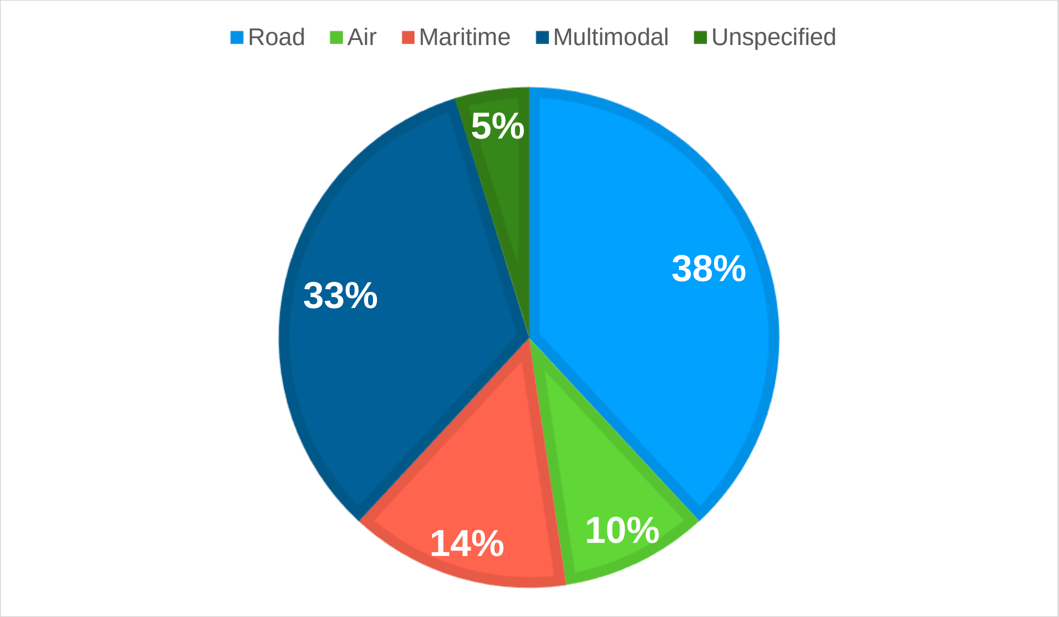


Figure 6 - Mode of transportation examined in reviews selected for tertiary research

Figure 7 shows the split between passenger and freight transportation in the reviewed studies. The distribution was even, with six studies focusing on each. Nine studies did not specify if they were referring to passenger or freight transportation or approached both.

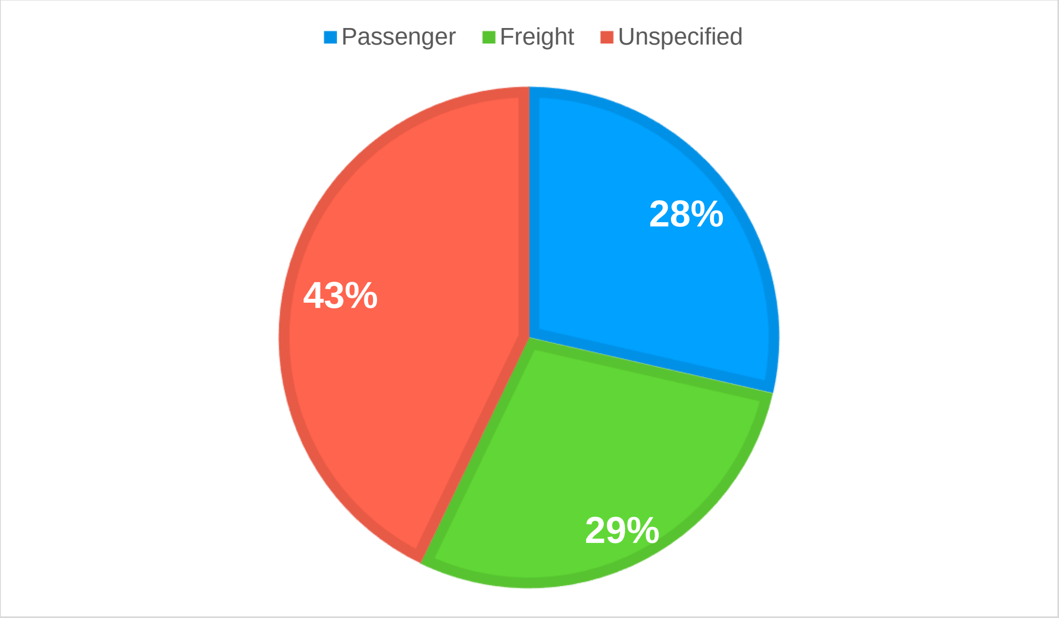


Figure 7 - Passenger/freight transportation split in reviews selected for tertiary research

Finally, Figure 8 illustrates the sustainability dimensions explored by each of the selected reviews. Almost three quarters of the studies focused exclusively on the environmental perspective of sustainability; three studies explored both the environmental and the social dimensions of sustainability; one study addressed both environmental and financial sustainability; and only two studies investigated the full triple bottom line of sustainability.

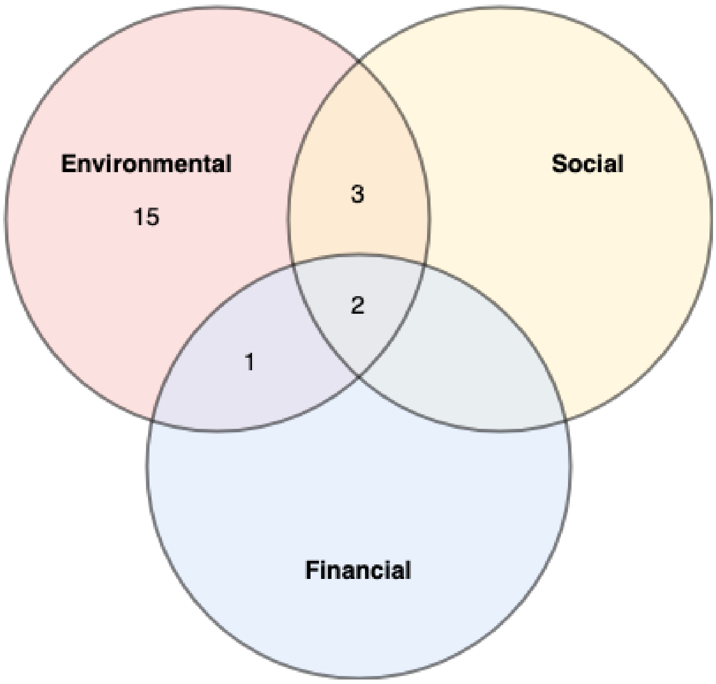


Figure 8 - Sustainability dimensions included in studies selected for tertiary review

4.2
Typology of carbon emissions reduction in transportation

Table 6 depicts a typology of carbon emissions reduction in transportation comprised of three main dimensions: enablers and barriers; benefits and disadvantages; and metrics. The majority of papers are concentrated in the dimension of enablers and barriers (16 papers), followed by metrics (11 papers), and finally benefits and disadvantages (3 papers). Each dimension is also further subdivided into categories. Within enablers and barriers, technological innovations was by far the most popular topic (11 papers), followed in descending order by regulatory and economic measures (6 papers), operational measures (5 papers), urban form and human behavior (4 papers) and strategy and stakeholder pressure (1 papers). Within benefits and disadvantages, climate change and other emissions and health both appeared in two papers, while competitive advantage and cost impact appeared in one paper each. Within metrics, life-cycle assessment and emissions modeling and inputs had 5 papers each, and measurement and performance indicators had 4 papers.

Subsections 4.3 through 4.5 further detail findings from each dimension and their respective categories. It is worth noting that the same category can be either a barrier or an enabler depending on the context, explaining why enablers and barriers comprise a single dimension. The same applies to the categories of benefits and advantages, which vary depending on context.

Table 6 - Typology of carbon emissions reduction in transportation

Dimensions	**Categories**	**Papers**
Enablers and barriers	Technological innovations	Li (2011); Hawkins *et al*. (2012); Faris *et al.* (2014); Bouman *et al.* (2017); Garcia & Freire (2017); Herold & Lee (2017); Requia *et al.* (2018); Salvucci *et al.* (2019); Meyer (2020); Oguntona (2020); Pilz *et al.* (2020)
	Operational measures	Bouman *et al.* (2017); Garcia & Freire (2017); Herold & Lee (2017); Meyer (2020); Oguntona (2020)
	Regulatory and economic measures	Eijgelaar (2011); Li (2011); Herold & Lee (2017); Lagouvardou *et al.* (2020); O’Mahony (2020); Oguntona (2020)
	Urban form and human behavior	Li (2011); Czepkiewicz et al. (2018); Salvucci *et al.* (2019); Hu & Creutzig (2021)
	Strategy and stakeholder pressure	Herold & Lee (2017)
Benefits and disadvantages	Climate change and other emissions	Kwan & Hashim (2016); Requia *et al.* (2018)
	Health	Kwan & Hashim (2016); Requia *et al.* (2018)
	Competitive advantage	Herold & Lee (2017)
	Cost impact	Herold & Lee (2017)
Metrics	Measurement and performance indicators	Franco *et al.* (2013); Kwan & Hashim (2016); Herold & Lee (2017); Meyer (2020)
	Emissions modeling and inputs	Smit (2010); Miola & Ciuffo (2011); Faris *et al.* (2014); Arioli *et al.* (2020); Oguntona (2020)
	Life-cycle assessment	Li (2011); Hawkins *et al.* (2012); Garcia & Freire (2017); Herold & Lee (2017); Meyer (2020)

4.3
Enablers and barriers

This subsection explores the enablers and barriers in obtaining carbon emissions reduction, which are identified in the literature and classified into five main categories: (i) technological innovations, (ii) operational measures, (iii) regulatory and economic measures, (iv) urban form and human behavior, and (v) strategy and stakeholder pressure. The author creates categories for better understanding and investigation, however, as stated by Bouman *et al.* (2017), individual measures (or adopting only measures of a specific category) are not enough to achieve significant GHG emissions mitigation. In the freight transportation scenario, Bouman *et al.* (2017) suggest that applying a combination of measures rather than picking an individual approach, would have the capacity to reach over 75% in GHG emission reductions by 2050 with current technologies. Bouman *et al.* (2017) also remark, however, that not all mitigation measures can be applied in combination with one another.

4.3.1
Technological innovations

Technological innovations include electrification, alternative fuels, vehicle design and manufacturing, communication technologies, and other indirect technologies with carbon mitigation potential. Breakthrough technologies have experienced rapid and continuous growth in recent years (Salvucci *et al.*, 2019). In a bibliometric analysis, Meyer (2020) identifies several technological innovations in the field of road freight transportation. In a review of air transportation, Oguntona (2020) compares the long-term potential of several aircraft fleet emissions mitigation measures and finds that approaches linked to technological innovations have the highest reduction potential. A review performed by Herold & Lee (2017), however, shows that little customer concern over energy efficiency demotivates companies from taking actions towards energy efficiency, which is further aggravated by lack of resources and knowledge.

Electrification has proven itself a hot topic over the last few decades. Some studies compare the environmental impacts of diesel, hybrid, and electric vehicles

(Hawkins *et al.*, 2012; Meyer, 2020). Hawkins *et al.* (2012) perform a comparison on the environmental impacts of electric vehicles (EVs) and conventional internal combustion engine vehicles (ICEVs). They find that while battery electric vehicles (BEVs) powered by coal electricity tend to perform better than conventional ICEVs, the same is not true when comparing coal-powered BEVs to high-efficiency ICEVs. However, when EVs are powered by natural gas or low-carbon energy sources, they outperform even most high-efficiency ICEVs in terms of global warming potential (Hawkins *et al.*, 2012). This shows that the environmental impact of EVs is highly depend on the energy source mix used for charging.

Garcia & Freire (2017) also draw attention to electricity generation sources and find that these have a significant impact on light-duty vehicle fleet emissions, with renewable energy sources presenting great potential. Moreover, while charging profile only slightly impacts GHG emissions at present, this scenario might change with an increase in battery size (Garcia & Freire, 2017). Important aspects to consider in charging profile are share of electricity in fleet energy demand and temporal variability (*i.e.*, charging time) (Garcia & Freire, 2017).

In the case of Nordic transportation, Salvucci *et al.* (2019) identify electrified roads, fuel cell and battery electric vehicles, and electric ferries as the technological innovations with the highest potential in the region. In the case of electrified roads and fuel cell vehicles, these could provide a valuable contribution in long distance freight transportation (Salvucci *et* al., 2019). Electrified ferries, on the other hand, draw attention due to ferries' significant participation in the region's maritime CO_2 emissions and due to the fact that several Nordic companies are already developing such ferries (Salvucci *et al.*, 2019). Salvucci *et al.* (2019) also highlight the importance of developing and analyzing model scenarios that include these technologies, so that the future demand of hydrogen and electricity can be accurately assessed.

In the case of India and other developing countries, however, the high cost of hydrogen and fuel cell technology is a major obstacle to commercial roll out (Li, 2011). Li (2011) also questions the sustainability of hydrogen energy, since fossil fuels are still the primary source of hydrogen production in many countries. Herold & Lee (2017) identify speculations surrounding battery technology and energy source sustainability as major barriers in the adoption of electric vehicle technologies by top management in companies.

Requia *et al.* (2018) perform a review on how clean EVs really are, addressing the concern of EVs simply relocating emissions from roads to power plants, among other concerns. Findings are that, even in scenarios with a high share of coal-based electricity, EVs still lead to decreasing CO_2 emissions (Requia *et al.*, 2018).

While most studies recognize the mitigation potential of biofuels (Bouman *et al.*, 2017; Garcia & Freire, 2017; Salvucci *et al.*, 2019; Oguntona, 2020), it is also encountered with hesitation in developed and developing economies alike (Li, 2011; Bouman *et al.*, 2017; Garcia & Freire, 2017; Salvucci *et al.*, 2019). In a review of Nordic transportation, Salvucci *et al.* (2019) observe considerable emissions reduction potential from the adoption of bioenergy, but are skeptical about future scenarios that rely heavily on the importation of this energy source. As a global trend towards decarbonization is observed, it is likely bioenergy demand will also grow in the future, raising questions about its availability (Salvucci *et al.*, 2019). As an alternative, Salvucci *et al.* (2019) recommend the development of a portfolio of domestic alternative fuel production chains, which will provide insights on domestic energy resources and storage capabilities. In the particular case of the Nordic scenario, forest-based and second-generation biofuel conversion as well as electrofuels are identified as promising domestic alternatives to bioenergy importation (Salvucci *et al.*, 2019). In the contrasting case of India, Li (2011) point out that biofuels may play a role in reducing the country’s dependence on imports, but will have a small or neutral contribution to climate change mitigation. Moreover, using farmable land for biofuel crop cultivation raises pressing concerns of food security in developing countries such as India (Li, 2011).

On a review of light-duty vehicle fleet emissions, Garcia & Freire (2017) also find significant potential for GHG emissions reduction through the use of biofuels. However, they classify this scenario as “optimistic" due to studies reviewed not accounting for land use changes and biomass resource availability factors, thus, suggesting this initiative be combined with other mitigation measures.

In the maritime transportation scenario, Bouman *et al.* (2017) review a series CO_2 emissions reduction measures and identify the use of biofuels as the one with the largest potential. However, they point out that reduced CO_2 emissions during combustion only partially represent the sustainability of biofuels. Agricultural factors, such as feedstock and crop rotation, as well as social and political concerns over land use all impact the mitigation potential and complexity of the problem (Bouman *et al.*, 2017).

Bouman *et al.* (2017) also identify LNG, hydrogen and renewable energy sources as lower emission alternatives to HFO-MGO bunker fuels. They suggest that current energy sources can be either completely substituted or only complemented by these alternatives (including biofuels), and that these changes will reduce emissions not only in use phase, but also in the entire fuel life cycle. Finally, regarding air transportation mode, Oguntona (2020) identifies promising future carbon reduction scenarios with the use of biofuels, and suggests policy-makers and stakeholders in the industry should focus on securing the availability and sustainability of this resource.

Garcia & Freire (2017) identify fuel consumption reduction, particularly vehicle weight reduction, as a key approach to reduce light-duty vehicle fleet GHG emissions, especially in internal combustion engine vehicle (ICEV) fleets. They remark, however, that vehicle weight reduction should be coupled with other measures (*e.g.*, powertrain efficiency improvements and biofuels) in order to reach full potential.

In the maritime transportation sector, Bouman *et al.* (2017) identify both hull design and power and propulsion as factors with significant CO_2 emissions mitigation potential. By adjusting hull dimensions, shape and weight, it is possible to improve ship hydrodynamic performance as to minimize water resistance (Bouman *et al.*, 2017). Regarding power and propulsion, Bouman *et al.* (2017) identify several technological innovations that can contribute to reduce emissions: kites, sails and other instruments to save energy consumption; hybrid power systems that can use complementary energy sources to reach an optimal use of resources; waste heat recovery; and power system and machinery design improvements. Regarding air transportation, Oguntona (2020) explores next-generation aircraft models and retrofits to existing aircraft towards fuel efficiency. On a bibliometric review, Meyer (2020) identifies after-treatment technologies as a strategy to reduce emissions.

Communication technologies — such as platooning and intelligent transportation systems — have been explored by several authors in recent years (Li, 2011; Faris *et al.*, 2014; Meyer, 2020). Platooning aims to reduce the aerodynamic drag of heavy-duty vehicles by using communication technologies to form closely-spaced groups of vehicles and as a result reduce carbon emissions (Meyer, 2020). Meyer (2020) draws attention to the need for more real-world applications of platooning to better understand the impact of this technology.

Faris *et al.* (2014) explore the environmental impact of Intelligent Transportation Systems (ITS) on vehicle fuel consumption and emissions. ITS use key evaluation metrics to evaluate performance and optimize vehicle routing based on information received through Inter-Vehicle Communication (IVC) (Faris *et al.*, 2014). Faris *et al.* (2014) find that ITS measures have significant impact on vehicle emissions. However, since ITS commonly optimizes to minimize transit time, emissions metrics are suboptimal and, in many cases, environmental impact might even be negative when transit time is improved (Faris *et al.*, 2014). When optimizing for transit time means opting for longer stop times or decreasing detour lengths, the optimization will be environmentally beneficial. (Faris *et al.*, 2014) However, when transit time optimization suggests short stop times or longer detours, environmental impact will be suboptimal (Faris *et al.*, 2014). Li (2011) also briefly addresses ITS technologies, highlighting their potential in optimizing traffic towards greater fluidity, thus reducing congestion, energy use and GHG emissions.

On a comparative analysis of additive and conventional manufacturing, Pilz *et al.* (2020) conclude that additive manufacturing reduces distances and quantity of products transported, thus reducing energy consumption and CO_2 emissions. However, Pilz *et al.* (2020) draws attention to the need for more studies in decentralized supply chains, particularly those based on LCA approach, for a more comprehensive understanding of the environmental impacts of additive manufacturing. Also concerning technologies that only indirectly impact transportation, Salvucci *et al.* (2019) identify carbon capture and storage as a strategy.

4.3.2
Operational measures

Operational measures appear in the literature as a carbon emission mitigation measure for road, air and water. Bouman *et al.* (2017) interestingly remark that while technical measures are sometimes limited in existing vehicles (*i.e.*, some measures cannot be applied as retrofit, and need to be built-in in entirely new vehicles), operational measures do not have such limitation.

Transport management and vehicle routing, carbon target setting, demand-side interventions, among others, were the identified operational carbon mitigation measures identifies and are detailed next. In a bibliographic coupling analysis performed by Meyer (2020) on the decarbonization of road freight transportation, vehicle routing is identified as the strongest theme. Within this theme, green vehicle routing and electric vehicle routing are the two main topics. A number of studies explore the relationship between emissions reduction and cost. Oguntona (2020) identifies air traffic management as an important measure in carbon mitigation through improved navigation and landing.

Regarding water, Bouman *et al.* (2017) identify six measures with high carbon mitigation potential in his review, out of which three can be classified as operational measures: economies of scale, speed, and weather routing and scheduling. Economies of scale have the power to significantly reduce fuel consumption, with a doubled cargo capacity representing only about 2/3 energy consumption increase (Bouman *et al.*, 2017). Speed reduction in the hydrodynamic boundary — boundary that delimits a steep increase in hull resistance — generates large fuel economies (Bouman *et al.*, 2017). Finally, weather routing and scheduling comprise optimizations in sailing route and speed as to minimize resistance and fuel consumption caused by weather, currents and waves (Bouman *et al.*, 2017).

Herold & Lee's (2017) review shows that local production, in contrast to overseas shipping, brings considerably lower emissions. Herold & Lee (2017) also investigate a number of operational measures related to transportation management that can aid carbon emissions reduction, such as container optimization, shipping speed increase, pooling supply chains, truck-sharing and carrier coordination. A number os studies reviewed by Herold & Lee (2017) identify potential emissions reduction in intermodal transportation.

Decreasing frequency and increasing load factor as an operational measure towards carbon mitigation appear in both Herold & Lee’s (2017) review on shipping and Oguntona’s (2020) review on air transportation. Herold & Lee (2017) highlight the potentially low cost impact of such measure. Oguntona (2020) also identifies early aircraft retirement as a mitigation measure for air transportation. Finally, Garcia & Freire (2017) identify demand-side interventions, such as reducing number of vehicles, travel demand or fleet growth, as measures with significant emission reduction potential. They highlight, however, that these interventions will decrease in mitigation potential as energy efficiency increases.

4.3.3
Regulatory and economic measures

Li (2011) identifies governance as an indispensable factor towards overcoming urban challenges, particularly in developing economies. Effective policies should be thorough, including multiple aspects relevant for sustainable development such as land use and transportation planning and infrastructure (Li, 2011). Policymaking should be done carefully, incorporating transportation strategy and involving relevant stakeholders at every step (Li, 2011). A sound governance is crucial in guaranteeing both urban development and climate change mitigation goals are reached (Li, 2011).

On a review conducted by Herold & Lee (2017), they find that government-imposed carbon policies are perceived as the greatest source of risk by managers in the transportation and logistics industry. Lagouvardou *et al.* (2020) and O’Mahony (2020) dive deeper into this topic. Oguntona (2020) identifies emissions trading, emissions limit setting, and fuel, route and airport taxes as carbon mitigation measures in aircraft fleets.

Lagouvardou *et al.* (2020) perform a review of Market-Based Measures (MBMs) for decarbonization in shipping. MBMs incentivize polluters to reduce emissions through financial means (such as market prices), based on the “polluter pays principle” (Lagouvardou *et al.*, 2020). Lagouvardou *et al.* (2020) identify several

MBMs for shipping in the literature that can be broken down into two main groups of variants: fuel levy and emission trading system (ETS). Fuel levy consists of a tax imposed on fuel, with the aim of inducing speed and fuel consumption reductions in maritime transport (Lagouvardou *et al.*, 2020). The level of levy, however, must be carefully designed, since a low levy may not provide enough incentive for companies to invest in sustainable technologies (Lagouvardou *et al.*, 2020). ETSs, on the other hand, consist of a central authority setting caps to emissions and requiring polluters to hold permits to carry out polluting activities. While regulatory bodies advocate the importance of international ETSs in climate change mitigation, industry stakeholders raise concerns on regulation and administration, impact on competition and carbon leakage (Lagouvardou *et al*., 2020).

O'Mahony (2020) performs a state-of-the-art review on carbon taxes. While carbon taxes are commonly regarded as a leading solution to reduce emissions, O'Mahony's (2020) findings show that carbon taxes are more effective as support mechanism to other carbon reduction initiatives rather than as a standalone solution. Moreover, O'Mahony (2020) identifies a gap in carbon tax implementation, mainly due political and social barriers, which may be scaled down through more moderate taxes.

Carbon offsetting is the practice of paying third-party providers to generate GHG savings — through projects that either reduce or absorb CO_2 — in order to compensate emissions (Eijgelaar, 2011). According to the UK Department of Energy and Climate Change (DECC, 2009), carbon offsetting is meant to compensate "unavoidable emissions". However, despite a number of tourism and aviation stakeholders agreeing that energy reduction should be the first-choice mitigation alternative, offsetting is still being used to justify growth (Eijgelaar, 2011)

In a review of voluntary carbon offsets in tourism emissions reduction (*i.e.*, non-mandatory carbon offsetting payed by the consumer), Eijgelaar (2011) finds that this is not an efficient mitigation measure, currently compensating for less than 1% of all aviation emissions (Eijgelaar, 2011). However, it is likely to remain a common practice due to lack of awareness and pressure on aviation and tourism industries to perform more structural changes (Eijgelaar, 2011).

4.3.4
Urban form and human behavior

In the case of urban dimension, Li (2011) and Salvucci *et al.* (2019) state that each urban area is particular in many ways — geography, demography, infrastructure, available resources, socioeconomic characteristics, *etc.* — and, as a result, have specific transportation challenges. Therefore, it is only expected that each be treated individually in modeling as well (Salvucci *et al.*, 2019). Li (2011) states that urban form is decisive in shaping energy consumption in cities and, as a result, GHG emissions as well.

Strongly influenced by urban form, human behavior and behavioral change policies play a key role in shaping modal choice and, as a result, transportation CO_2 emissions (Li, 2011; Salvucci *et al.*, 2019). However, as pointed out by Salvucci *et al.* (2019), many energy-economy-environmental-engineering (E4) models still fail to take into account this paramount dimension.

According to Li (2011), urbanization typically follows economic development and is essential for sustainable economic growth. In developing countries, cities are usually responsible for a high share of economic activities and Li (2011) predicts metropolitan cities will be responsible for an increase in transportation energy demand in these economies. Transportation systems are an intrinsic and essential part of cities and should be regarded as such by local government (Li, 2011). While transportation planning is many times made independently from other urban services, Li (2011) calls out that an integrated planning is of extreme importance for transportation development. Multiple synergies can occur between transportation and land use, for example, and thus integrated planning could benefit both (Li, 2011).

Salvucci *et al.* (2019) also observe that urban planning can have a significant impact in transportation, including driving patterns and modal shift. They observe that varying granularity levels when assessing regions — evaluating urban dimension as well country dimension, for example — might provide valuable insights (Salvucci *et al.*, 2019).

While conducting a review on the relationship between urban form and long-distance leisure travel, Czepkiewicz *et al.* (2018) find that people who reside in larger, denser and more central neighborhoods have a greater tendency to go on long-distance leisure travel than people who live in suburban or rural areas. This relationship applies particularly to air and international travel (Czepkiewicz *et al.*, 2018). One theory raised by Czepkiewicz *et al.* (2018) surrounding this phenomenon is that access to transport infrastructure is a determinant in long-distance leisure travel, however current evidence is still not enough to confirm this theory. Other theories raised by Czepkiewicz *et al.* (2018) concerning this relationship include the rebound effect, escape hypothesis and sociopsychological factors.

Salvucci *et al.* (2019) identify income, GDP per capita, and fuel prices as determinants in modeling vehicle ownership and mileage; and travel time budget and transport infrastructure as key factors in shaping modal shift (Salvucci *et al.*, 2019). If planned correctly, effective policies promoting modal shift can also contribute to reducing car ownership (Salvucci *et al.*, 2019). New mobility trends such as autonomous vehicles and mobility as a service (MaaS), however, have yet to be properly modeled in regards to their impact in car ownership and mileage as well as congestion (Salvucci *et al.*, 2019).

An important aspect to consider in vehicle ownership is the phenomenon of urban sprawl. Li (2011) remarks that both American and European cities have experienced a significant increase in area, which is disproportional to a not as high population growth, creating a need for private vehicle ownership. A similar trend can also be observed in developing countries in recent years (Li, 2011). Higher urban density, on the other hand, is associated with lower transportation-related emissions, but with higher household energy demand (Li, 2011).

Li (2011) also draws attention to the reinforcing loop dynamics between road infrastructure and car ownership. Road infrastructure is built as a response to increased car ownership; better road infrastructure in turn drives attractiveness in buying new vehicles (Li, 2011). In the case of developing economies, economic growth leading to greater per capita incomes will cause growing car ownership (Li, 2011). For Li (2011), improving the quality, public perception and lowering costs and time of public transportation are key to reducing private car ownership and associated fuel consumption and carbon emissions.

Hu & Creutzig (2021) perform a systematic review on shared mobility in China, including ride hailing, car sharing and bike sharing. While shared mobility is intended to reduce car ownership and increase the use efficiency of vehicles, there is still a lot of uncertainty surrounding its relationship with public transportation (Hu & Creutzig, 2021). On the one hand, the flexibility of shared mobility can turn it into a major feeder of public transportation (thus, supporting public transportation efforts) (Hu & Creutzig, 2021). On the other hand, other characteristics (i.e., price, convenience, and quality) might lead to public transport cannibalization, causing a potential rebound effect in GHG emissions (Hu & Creutzig, 2021). Hu & Creutzig (2021) also draw attention to the association between shared mobility and digitalization and electrification, particularly in China.

4.3.5
Strategy and stakeholder pressure

Herold & Lee (2017) identify competitive advantage as an emerging theme in the logistics and transportation carbon management literature. They find that efforts towards carbon reduction are strongly tied to business strategy, and that improving sustainability performance can be key in differentiation. Disclosure and communication with stakeholders, however, is extremely important so that carbon reduction can be effective as a competitive advantage. Studies reviewed by Herold & Lee (2017) also show that while stakeholder pressure is more powerful than governmental pressure, it is not enough to motivate companies if carbon reduction is not in line with long-term strategy.

They also find that alignment between retailers and regulatory forces and subsequent implementation of carbon policies present a great challenge that might impact the success of such policies (Herold & Lee, 2017). Moreover, the effectiveness of carbon pricing schemes are brought to question, once their cost are usually not meaningful enough to drive behavioral changes (Herold & Lee, 2017).

Herold & Lee (2017) investigate carbon target setting, and find that companies adopt many different carbon target setting approaches and that, most of the times, targets are set on a corporate level, without a deeper understanding of reduction potentials at an operational level. Moreover, regarding the relationship between emissions reduction and cost, Herold & Lee (2017) identify that ambitious carbon reduction targets cannot be reached with limited investments.

4.4
Benefits and disadvantages

Most studies reviewed focus on the enablers and barriers and metrics dimensions of carbon emissions reduction. In most studies, carbon emissions reduction and climate change mitigation are identified as intrinsic benefits, and further co-benefits or disadvantages of emissions reduction are not explored. In their review of carbon management in transportation, Herold & Lee (2017) highlight paucity of studies investigating the performance outcomes of the adoption of mitigation strategies. Kwan & Hashim (2016) are an exception, identifying secondary benefits of carbon emissions reduction through a review of the co-benefits of mass public transportation. A few other studies touch on outcomes, such as cost impact or costs and carbon emissions trade-off (Herold & Lee, 2017), but very superficially.

This indicates a gap in research concerning the post-implementation phase of carbon mitigation strategies and confirms the infancy of carbon concern. Different dimensions of sustainability are portrayed in the literature as an antecedent, determinant, mediator or moderator of outcomes and of environmental performance in studies reviewed by Magon *et al.* (2018) in more mature studies of sustainability, differently than for the literature on carbon emissions outcomes and performance measures.

While this review focused specifically on CO_2 emissions reduction, many carbon mitigation actions also reduce other emissions and air pollution in general. One example is the reduction of black carbon through the implementation of mass public transportation, which is harmful for climate change and air pollution health implications (Kwan & Hashim, 2016). Carbon monoxide, nitrogen oxides and volatile organic components are other air pollutants that might also be reduced through mass public transportation (Kwan & Hashim, 2016).

Electric vehicles, a technology commonly associated to GHG mitigation, may also cause significant impact on gaseous pollutants — such as nitrogen oxides, VOC and SO_2 — and moderately reduce particulate matter emissions (Requia *et al.*, 2018). On a review focused on EVs, Requia *et al.* (2018) raise the debate on EVs shifting air pollution — rather than inherently reducing it — in countries mainly powered by fossil fuels. In such scenarios, it may be argued that emissions are simply transferred from vehicle tailpipes in roads (predominantly urban areas) to power plants (usually located in suburban or rural areas) (Requia *et al.*, 2018). Spatial distribution will be a key determinant on health impact in these cases, reducing exposure in countries where the majority of the population is concentrated in cities and only shifting it in countries with a more even population distribution (Requia *et al.*, 2018). However, this might raise issues of fairness (Requia *et al.*, 2018). Requia *et al.* (2018) state that, in order to obtain significant impact in health and emissions reduction, EVs must be coupled with clean energy sources. Specific mitigation measures, such as mass public transportation, might generate secondary benefits to carbon emissions reduction, such as fewer traffic injuries and increased physical activities (Kwan & Hashim, 2016). However, secondary benefits are beyond the scope of this study.

In Subsection 4.3.5, corporate strategy is identified as a determinant in the adoption of carbon mitigation measures by companies, indicating potential associated benefits to emissions reduction in positive cases. One of such benefits is competitive advantage. As expressed by Herold & Lee (2017), environmental sustainability can be an important differentiation strategy. However, in order to reap its full benefits, carbon reduction strategies must be tied to communication and transparency with stakeholders (Herold & Lee, 2017). When investigating carbon target setting, Herold & Lee (2017) suggest that serious emissions reductions can only be achieved with investment.

4.5
Metrics

This section reviews indicators of measurement and performance indicators, emissions modelling and inputs, and life-cycle assessments.

Emission factors (EF) are used in emission models to quantify the contribution of different inputs (*e.g.*, distance, energy, fuel) towards pollution (Franco *et al.*, 2013). Franco *et al.* (2013) perform a review of experimental approaches used to measure road vehicle emissions and develop EFs. They review measurement techniques under controlled environments (*i.e.*, chassis and engine dynamometer testing) and under real-world conditions (*i.e.,* remote sensing, road tunnel studies and portable emission measurement systems (PEMS)). Findings are that controlled environment techniques are more mature but also more expensive, while real-world conditions techniques provide a more accurate reflection of reality but also have larger variability that must be accounted for (Franco *et al.*, 2013).

Kwan & Hashim (2016) highlight the importance of incorporating speed into emissions calculations, since calculations based solely on distance might underestimate emissions, ignoring traffic congestion, for example. Moreover, Herold & Lee (2017) and Meyer (2020) identify a number of studies focused on emissions measurement in their respective reviews. Several studies focus on quantifying emission reductions before and after the implementation of mitigation measures (Herold & Lee, 2017; Meyer, 2020). Herold & Lee (2017) also find a number of studies that investigate the trade-off relationship between costs and emissions. Smit *et al.* (2010) explores different types of traffic emission models and performs a meta-analysis of studies validating these.

Arioli *et al.* (2020) compare different approaches to estimate transport GHG emissions. They find that most studies adopt a top-down approach, usually using national or municipal-level statistics. On a slightly less frequent basis, many studies also use a bottom-up approach, using large volumes of data from sometimes multiple datasets. While this is the most accurate method, it can also be the most challenging in terms of data availability (Arioli *et al.*, 2020). On-site measurements were the least common GHG inventory method (Arioli *et al.*, 2020).

Arioli *et al.* (2020) state that data availability and the aim of the GHG inventory should be considered when choosing the best approach. For exclusively a characterization of emissions, a top-down approach would be the most recommended, however, for a characterization coupled with an action plan, the bottom-up approach provide better results (Arioli *et al*., 2020). Arioli *et al.* (2020) also highlight the potential contribution that technology and data advancements (*e.g.*, big data, GPS navigators, mobile phones and social media data) can bring to urban mobility if fully explored.

Similarly, Miola & Ciuffo (2011) compare bottom-up and top-down methods in estimating air emissions from shipping. Miola & Ciuffo (2011) remark the high level of discrepancies in results from both approaches — attributed mainly to information sources — and introduce the use of multiple data sources simultaneously as a workaround towards greater accuracy in results.

Faris *et al.* (2014) perform a review of vehicle fuel consumption and emissions modeling combined to Intelligent Transportation Systems (ITS) and explore the different scales of modeling: microscopic, macroscopic and mesoscopic. They find that while microscopic models provide greater accuracy, macroscopic models are indicated for aggregate emissions inventory estimations. Mesoscopic models are halfway between the other two in terms of accuracy and complexity. Similar to Arioli's *et al.* (2020) classification of approaches, Faris *et al.* (2014) classify empirical and statistical modeling approaches (respectively bottom-up and top down approaches in Arioli *et al.* (2020)). They conclude that mesoscopic and empirical models are the most indicated for ITS network optimization and environmental impact assessment. Oguntona (2020) reviews nine approaches to modeling aircraft fleet development, comparing long-term fleet-level emissions of different carbon mitigation measures.

Hawkins *et al.* (2012) utilize a life-cycle inventory (LCI) approach to compare the environmental impacts of electric vehicles and conventional internal combustion engine vehicles (ICEVs). They find that the GHG of electric vehicles is highly dependent on the use phase, with this phase being responsible for 60-90% of life cycle global warming potential for battery electric vehicles (BEVs) powered by fossil-based electricity sources. However, more comprehensive LCIs including all phases of electric vehicle life-cycle is still needed to understand the full environmental impact of these vehicles (Hawkins *et al.*, 2012).

LCAs are typically centered on the life-cycle of a given product, and fail to capture transient effects caused by the introduction or replacement of products and technologies (Garcia & Freire, 2017). Having this in mind, Garcia & Freire (2017) take LCA a step further and adopt a fleet-based life-cycle approach, capable of capturing these dynamics, to perform a review of light-duty transportation. They find, however, that most reviewed studies fail to include the entire fleet life-cycle, usually overlooking the production and disposal phases.

Li (2011) advocated the need for cost-benefit analyses using LCA approach in urban transportation, as these allow for a holistic assessment of costs incurred in private versus public transportation. Herold & Lee (2017) and Meyer (2020) also review several studies that incorporate LCAs.

4.6
Synthesis framework

Figure 9 presents a framework synthesizing the results from the tertiary review and illustrating the interactions between the different key factors in carbon emissions reduction in transportation.

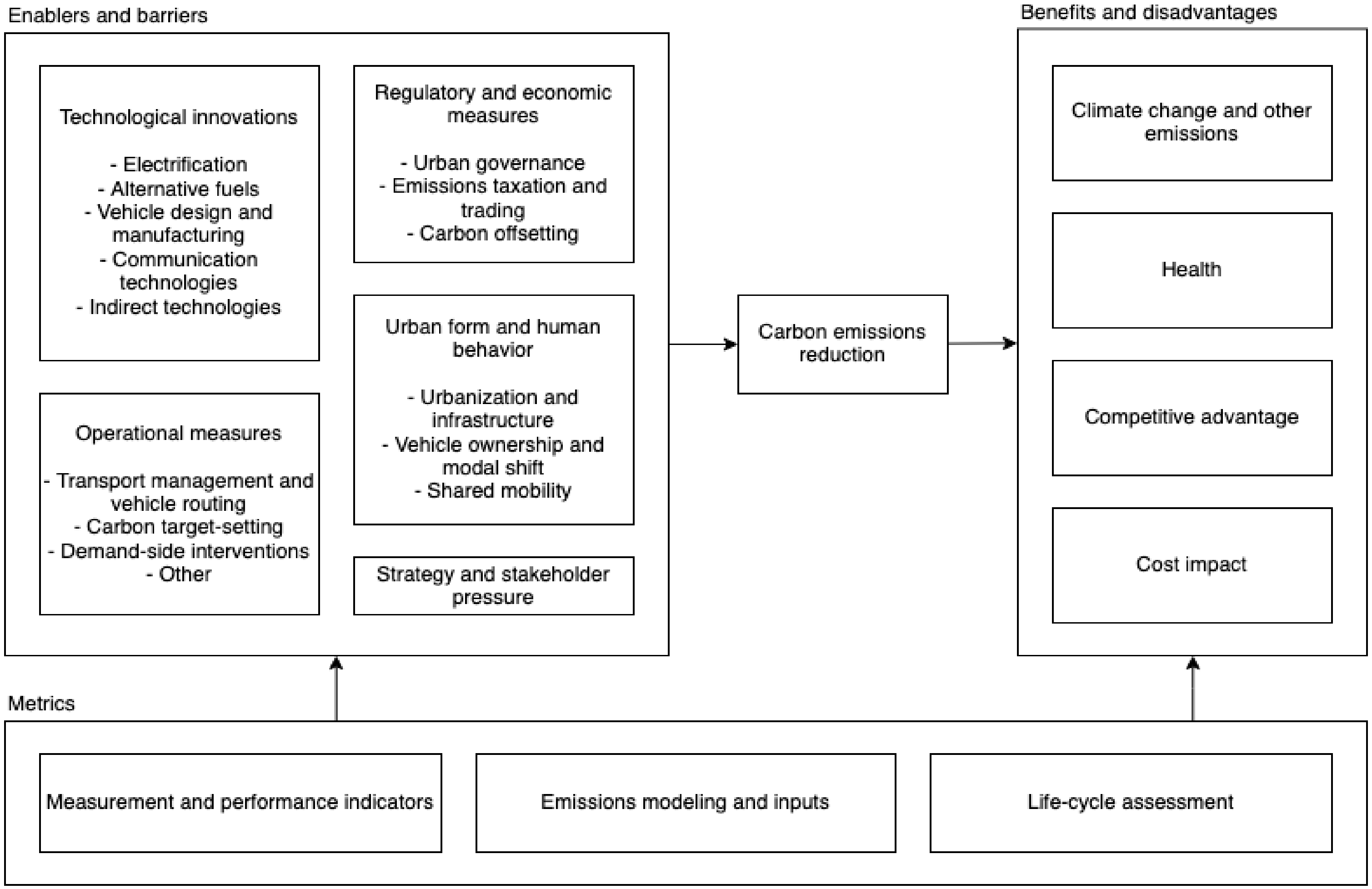


Figure 9 - A synthesis framework for enablers, barriers, benefits, disadvantages and metrics for carbon emissions reduction in transportation

Focusing on the theme of carbon emission reductions in transportation, the first step in the framework development was to identify key factors surrounding this topic in the reviewed literature. These factors were then classified into three major categories: enablers and barriers, benefits and disadvantages and metrics.

Factors that fell into the enablers and barriers category were any factors that influenced or determined carbon emissions reduction, either by acting as an enabler and potentializing mitigation or by acting as a barrier and preventing reduction. Benefits and disadvantages were factors that were an outcome or consequence of emissions reduction, both positive and negative, but did not influence emissions reduction directly. Finally, metrics included any method or approach to measure or quantify carbon mitigation. These could be applied to either model the potential impact of factors influencing mitigation or to measure real-life effects of a given strategy.

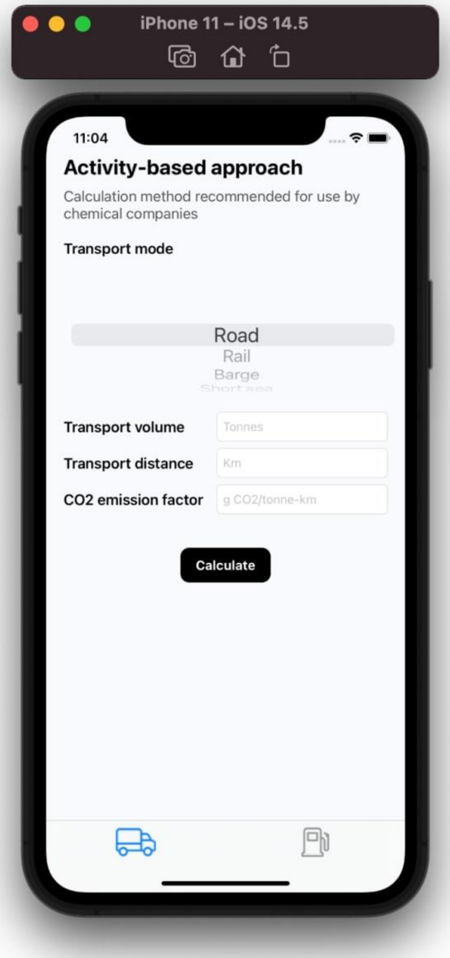
4.7
CO_2 emissions calculator

Practitioners in the transportation sector are increasingly under pressure from stakeholders and policymakers to decrease their carbon footprint. Having this in mind, awareness of carbon emissions is essential in order to be prepared for changes and strategize for the future. With the goal of providing an accessible, quick and easy way of estimating CO_2 emissions for practitioners involved in the transportation sector, the author developed an iOS mobile app for this purpose. Section 4.7.1 describes the mobile app and its views and Section 4.7.2 exemplifies a toy case of the CO_2 calculator.

4.7.1
Mobile app

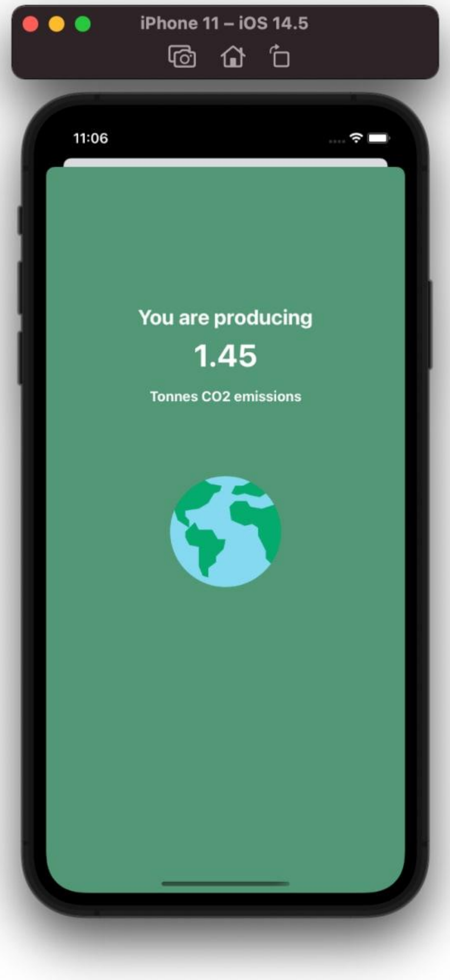
The app has three main views: activity-based approach view, energy-based approach view, and results view. The activity-based approach view (which can be selected by tapping the truck on the app tab bar), in Figure 10, is recommended for use by chemical companies. It uses transportation activity data to calculate CO_2

emissions, so that chemical companies can gain insights on fuel efficiency. Four inputs are required to calculate emissions using this approach: transport mode, transport volume, transport distance and CO_2 emission factor. The user can pick between 11 transport modes — road, rail, barge, short sea, intermodal road/rail, intermodal road/barge, intermodal road/short sea, pipelines, deep-sea container, deep-sea tanker, and airfreight — and based on the selected transport mode the app will automatically provide a CO_2 emission factor based on ECTA & CEFIC (2011). CO_2 emission factor is represented in g CO_2/tonne-km and may be edited if the user would like to use a value different from the suggested one. Transport volume is asked in tonnes and transport distance in km. After inputing the required information, tapping the "calculate" button will lead the user to the results view (Figure 11), which will show the estimated CO_2 emission in tonnes CO_2.



Calculation method recommended for use by chemical companies

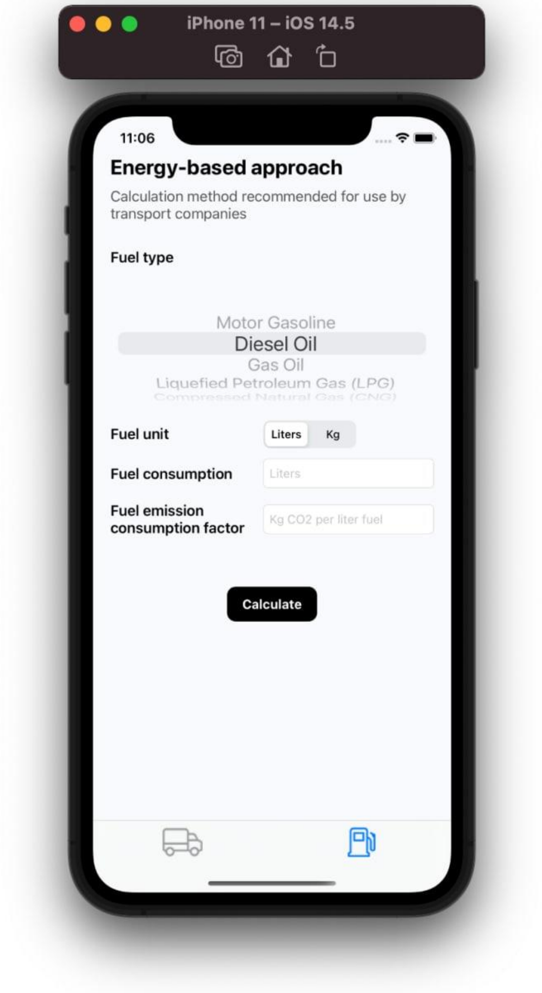
Figure 10 - CO_2 calculator app activity-based approach view



You are producing
1.45
Tonnes CO2 emissions

Figure 11 - CO_2 calculator app results view

The energy-based approach view (which can be selected by tapping the fuel pump on the app tab bar), in Figure 12, on the other hand, is recommended for use by transportation companies. It uses transportation fuel consumption data to calculate CO_2 emissions, so that transportation companies can understand their emissions based on the amount of fuel they are consuming. Four inputs are required to calculate emissions using this approach: fuel type, fuel unit, fuel consumption and CO_2 emission factor. The user can pick between 9 fuel types — motor gasoline, diesel oil, gas oil, liquefied petroleum gas (LPG), compressed natural gas (CNG), jet kerosene, residual fuel oil, biogasoline, and biodiesel — and based on the selected fuel type the app will automatically provide a fuel unit and CO_2 emission factor based on ECTA & CEFIC (2011). Fuel unit can be either liters or kilograms. Fuel unit for CNG, jet kerosene and residual fuel oil is kilograms, while unit for all other fuel types is liters. CO_2 emission factor will adapt between kg CO_2 per liter fuel or kg CO_2 per kg fuel according to the selected fuel type. Like fuel unit, CO_2 emission factor can also be edited if the user would like to use a value different from the suggested one. Fuel consumption should be inputed in liters or kilograms, according to the selected unit. After inputing the required information, tapping the “calculate" button will lead the user to the results view (Figure 11), which will show the estimated CO_2 emission in tonnes CO_2. The CO_2 calculator app is available for download at the App Store under the name of “LogCO_2: Carbon Emissions Calculator”. The software will also be submitted for registration at the Brazilian INPI institute.



Energy-based approach

Calculation method recommended for use by transport companies

Fuel type: Diesel Oil

Fuel unit: Liters

Fuel consumption

Fuel emission consumption factor

Figure 12 - CO_2 calculator app energy-based approach view

4.7.2
Toy case

AZ Logistics is a small carrier located in France. They have a small fleet of six trucks fueled by diesel. They struggle with competition from larger companies and are considering a switch from diesel to biodiesel in order to differentiate themselves from competitors and become more attractive to clients interested in sustainability.

Before making the switch, however, the owner of AZ Logistics wants to gather as much information as possible on the benefits and disadvantages of using biodiesel, with limited resources. The owner knows that diesel, the fuel currently being used by AZ Logistics, costs around 1.40 euros per liter while biodiesel is priced higher at 1.60 euros a liter. He has also learned from colleagues in the industry that biodiesel is slightly less efficient than diesel, and expects a fuel consumption increase of around 10%. The owner estimates that AZ Logistics' current fleet consumes on average 120,000 liters of diesel each year, which would equal to roughly 132,000 liters of biodiesel per year. Using simple math, he calculates a yearly investment of 43.2K euros for substituting diesel to biodiesel.

In order to understand the environmental impact of the switch, the owner uses LogCO_2 app to estimate CO_2 emissions using the energy-based approach (recommended for transportation companies). He inputs fuel type (diesel oil/biodiesel), unit (liters) and consumption and uses the recommended emission factor (*i.e.*, 2.9 kg CO_2/liter for diesel oil and 1.9 kg CO_2/liter for biodiesel). He finds that AZ Logistics' current emission using diesel oil is of 348 tons CO_2 per year and predicts a yearly 251 tons CO_2 using biodiesel. He also knows that France charges around 45 euros per ton CO_2 emissions in carbon taxes, so a 97 ton CO_2 decrease in emissions would translate to 4.4K euros savings in carbon taxes, bringing the necessary investment down to 38.8K euros per year.

The owner also uses LogCO_2 app to simulate scenarios where only part of the fleet would perform a biodiesel substitution. He finds that a scenario where three trucks would continue to use diesel and three trucks would use biodiesel would translate to 48 tons CO2 reduction and 21.6K euros additional fuel cost, minus 2.2K savings in carbon taxes.

Diesel oil price was taken from Auto News (2021) and France carbon taxes were taken from Tax Foundation (2021).

5
Discussions

Regarding the papers selected for the tertiary review, while some papers identified explored transportation in general, most papers focused on only one transportation mode (road, air or water). Road was the most prolific transportation mode and rail surprisingly was not the main focus of any of the studies, although it appeared briefly in some studies that explored more than one transportation mode. The studies were evenly distributed between investigating passenger and freight transportation. The methodology adopted by each of the selected reviews are, in order of frequency: systematic review, literature review, critical review, meta-analysis and state-of-the-art review.

Enablers, barriers, benefits, disadvantages and metrics in carbon emissions reduction were identified and a comprehensive framework was built. Technological innovations, operational measures, regulatory and economic measures, urban form and human behavior, and strategy and stakeholder pressure were the main enablers and barriers identified. It is worth noting that most of these factors can act as either enablers or barriers depending on context, emphasizing the relevance of a contingency view of carbon emission in transportation. There is not a “one-size-fits-all” type policy or mitigation measures, strategies, programs, and results varies depending on countries and programs due, among others to the country’s development levels, different energy matrices, configuration of transportation modes and prevalent economic activity. Regarding benefits and disadvantages, the same was true: most outcomes could be seen as both benefits and disadvantages and therefore were not split into two separate groups. Benefits and disadvantages identified were climate change and other emissions, health, competitive advantage and cost impact. Finally, measurement and performance indicators, emissions modeling and inputs and life-cycle assessment were classified as metrics, and used to measure the carbon emissions reductions. The identification of such factors answers RQ1: “What are the main barriers, enablers, benefits and disadvantages of carbon emission reduction in transportation?”. The development of a typology answers RQ2: “What are the main dimensions or categories utilized to describe the initiatives for carbon mitigation in the transportation sector?”.

Another out striking result was the unbalanced nature of the relationships among the categories. Figure 13 attempts to illustrate the relationships between the categories identified in Chapter 4 - Results. The size of each node represents the number of articles addressing each of the themes and edges represent at least two articles addressing both the connected nodes. Ticker edges mean more articles address both nodes.

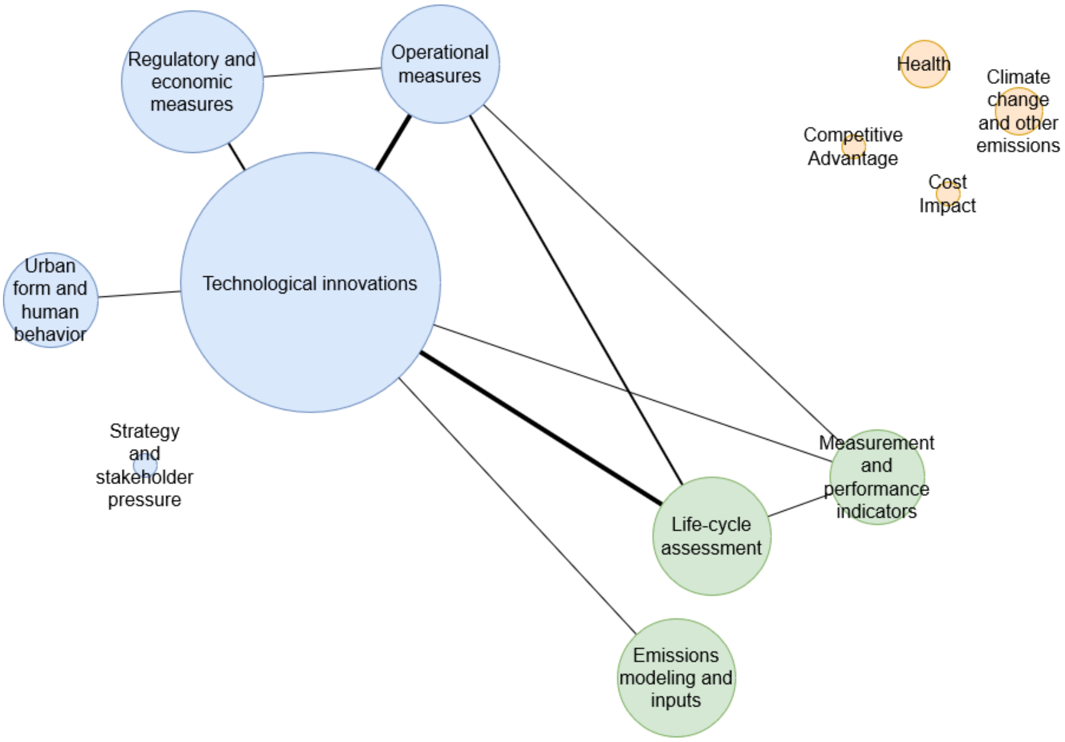


Figure 13 – Relationship between enablers, barriers, benefits, disadvantages and metrics in carbon emissions reduction

While enablers, barriers, benefits and disadvantages were all present in the literature, it was clear that they were not all explored to the same depth: 16 papers examined enablers and barriers, whilst only three papers analyzed benefits and disadvantages. Most studies assume carbon emissions reductions are fundamentally beneficial and, as a result, fail to identify potential disadvantages or co-benefits. This finding is in line with one criticism of Multi-Level Perspective identified by Geels (2019): “Assuming that ‘green’ innovations are intrinsically positive, they [transitions scholars] rarely address how much sustainability improvement they offer and if this would be sufficient to address persistent environmental problems at the speed required”.

Under the lens of contingency theory, however, it is possible to observe the importance of exploring the benefits and disadvantages of carbon emissions reduction initiatives. We observe that both landscapes and mitigation initiatives are well explored, but there is still much to learn from the outcomes of these relationships. One interesting example is the case of biofuels: while experiments have shown biofuels produce less tailpipe emissions than fossil fuels, their use might have backfiring effects depending on the context they are applied to. In developing countries, for example, biofuels might have a negative impact on land use, while in developing countries relying on importations might be a risk to energy security. This shows that understanding the outcomes of mitigation initiatives is necessary to understand their fit in different landscapes and, thus, gain valuable insights on their effectiveness and potential success. The relevance of sustainability-related issues central to the analysis of carbon emissions in transportation can be seen in Magon *et al.* (2018) systematic literature review of the inter-relationships between sustainability and performance. It also comes to show that there is no universal mitigation strategy, valid for all types of landscapes. Building on top of contingency theory, Bouman *et al.* (2017) also state that individual measures are not enough to achieve significant GHG emissions mitigation. Having this in mind, exploring the relationship between different carbon reduction initiatives might also be interesting in achieving meaningful results. Regarding the fourth and last postulate of contingency theory applied to transportation carbon emissions, we see that there is increasing interest from the academy in measuring carbon emission reduction. Simulations of carbon emissions in inbound logistics operations in an emerging economy can be found, for example, in Muñoz-Villamizar et al. (2021). Developing metrics to quantify outcomes other than emissions is still in its infancy.

Another interesting finding was that all reviewed studies approached the environmental aspect of sustainability and the majority focused on this perspective only. Only a few studies investigated the social or financial aspects of sustainability or the full triple bottom line. This is consistent with the multi-level perspective approach to socio-technical transitions and indicates we are at the beginning of a transition process, which can still decades to completely unfold. Currently, we observe multiple niches in transportation starting to appear, but still lacking the maturity necessary to overcome challenges and barriers and transform or replace the existing regimes. New initiatives are still very focused on reaching an energetic matrix with less carbon, but social and economic implications are not yet fully explored. The typology of carbon emissions reduction in transportation and resulting synthesis framework provide a snapshot of the current state of sustainable transitions.

6
Conclusion

This study conducted a systematic literature review that resulted in the selection and examination of 21 review papers in the area of carbon emissions transportation, covering a total of 2,574 primary research papers. Enablers, barriers, benefits, disadvantages and metrics in carbon emissions reduction were identified and a comprehensive framework was built. This study also produced a mobile app that enables practitioners in the transportation and chemical industries to quickly and easily estimate CO2 emissions. Practical implications from the review and mobile app, and limitations and directions for future research can be found in this concluding section.

6.1
Practical implications

This study combines socio-technical transitions theory and contingency theory to the field of transportation carbon emissions. The result is a comprehensive view of the current state of carbon emissions reduction initiative in transportation with a critical view of the outcomes that result from different environment-initiative relationships.

The identification of enablers, barriers, benefits, disadvantages and metrics currently found in the literature provides researchers and practitioners alike with a better understanding of the current state-of-the-art in carbon reduction in the transportation sector, providing a "snapshot" of the socio-technical transition state we are in. The organization of such into a typology and synthesis framework of carbon emissions reduction in transportation allows a better understanding of the different categories that are being explored in each dimension and uncovers the need for a greater focus in the benefits and disadvantages of mitigation initiatives applied to different scenarios.

The development of a free mobile iOS application that calculates CO_2 emissions in transportation provides an easy and accessible tool for transportation and chemical companies to measure their carbon impact. It is a powerful tool especially for small businesses that currently do not have the means to invest resources in exploring environmental impacts. The application facilitates awareness on the different emission levels associated to different transportation modes and fuel types for both practitioners and academics.

6.2
Future research

As shown by contingency theory applied to carbon emissions in transportation, there is a paucity on research on the outcomes of carbon emissions reduction initiative. Therefore, investigating the benefits and disadvantages of initiatives in different scenarios comes as a recommendation for future research. Going beyond contingency theory, an investigation on the synergies between different measures (*i.e.*, initiative-initiative fit) would also be interesting and a valuable finding for companies and policy-makers to devise strategies.

In this dissertation, socio-technical transitions theory and contingency theory are introduced as a backdrop to understanding carbon mitigation strategies in transportation. While socio-technical transitions provide a wider context to individual measures, it often focuses on the transition itself and fails to capture the aftermath of such. Contingency theory, on the other hand, provides are more focused view that incorporates outcomes. Having this in mind, further exploration of a combination of both theories would be an interesting topic for future research.

Finally, we observe that the larger part of the existing literature on sustainability in transportation is biased towards developed countries. The importance of landscape, however, is shown by contingency theory and, therefore, in order to reach significant carbon reduction worldwide devising strategies aimed at developing economies is as important as analyzing the developed scenario.

7
References

AMUNDSON, S.D. Relationships between theory-driven empirical research in operations management and other disciplines. **Journal of Operations management**, v.16, n.4, p. 341-359. 1998.

ARIOLI, M. S. et al. The evolution of city-scale GHG emissions inventory methods: A systematic review. **Environmental Impact Assessment Review**, v.80, p.106316. 2020.

BACHARACH, S.B. Organizational theories: Some criteria for evaluation. **Academy of management review**, v.14, n.4, p. 496-515. 1989.

BERGEK, A. et al. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. **Research policy**, v.37, n.3, p. 407-429. 2008.

BOUMAN, E. A. et al. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping–A review. **Transportation Research Part D:** Transport and Environment, v.52, p. 408-421. 2017.

CARLSSON, B.; STANKIEWICZ, R. On the nature, function and composition of technological systems. **Journal of evolutionary economics**, v.1, n.2, p. 93-118. 1991.

CHAPMAN, L. Transport and Climate Change: A Review. **Journal of Transport Geography**, v.15, n.5, p. 354-367. 2007.

COLQUITT, J.A.; ZAPATA-PHELAN, C.P. Trends in theory building and theory testing: A five-decade study of the Academy of Management Journal. **Academy of management journal**, v.50, n.6, p. 1281-1303. 2007.

COOPER, H.; HEDGES, L. V. Research Synthesis as a Scientific Process. In: COOPER, H.; HEDGES, L. V.; VALENTINE, J. C. (Eds.). **The handbook of research synthesis and meta-analysis**. New York: The Russell Sage Foundation, 2009.

COOPER, H. **Research synthesis and meta-analysis:** a step-by-step approach. 4.ed. Thousand Oaks: Sage Publications, 2010.

CZEPKIEWICZ, M.; HEINONEN, J.; OTTELIN, J. Why do urbanites travel more than do others? A review of associations between urban form and long-distance leisure travel. **Environmental Research Letters**, v.13, n.7, p. 073001. 2018.

DONALDSON, L. **The contingency theory of organizations**. Sage, 2001.

DRAZIN, R.; VAN DE VEN, A.H. Alternative forms of fit in contingency theory. **Administrative science quarterly**, p. 514-539. 1985.

ECTA, CEFIC. **Guidelines for Measuring and Managing CO2 Emission from Freight Transport Operations**. 2011.

EIJGELAAR, E. Voluntary carbon offsets a solution for reducing tourism emissions? Assessment of communication aspects and mitigation potential. **European Journal of Transport and Infrastructure Research**, v.11, n.3. 2011.

FARIS, W.; RAKHA, H.; ELMOSELHY, S. A. Impact of Intelligent Transportation Systems on Vehicle Fuel Consumption and Emission Modeling: An Overview. **SAE International Journal of Materials and Manufacturing**, v.7, n.1, p. 129-146. 2014.

FERRER, A.L.C.; THOMÉ, A.M.T.; SCAVARDA, A.J. Sustainable urban infrastructure: A review. **Resources, Conservation and Recycling**, v.128, p. 360-372. 2018.

FRANCO, V. et al. Road vehicle emission factors development: A review. **Atmospheric Environment**, v.70, p. 84-97. 2013.

GARCIA, R; FREIRE, F. A review of fleet-based life-cycle approaches focusing on energy and environmental impacts of vehicles. **Renewable and Sustainable Energy Reviews**, v.79, p. 935-945. 2017.

GEELS, F.W. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. **Research policy**, v.31, n. 8-9, pp.1257-1274. 2002.

GEELS, F.; RAVEN, R. Non-linearity and expectations in niche-development trajectories: ups and downs in Dutch biogas development (1973–2003). **Technology Analysis & Strategic Management**, v.18, n.3-4, p. 375-392. 2006.

GEELS, F.W. A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. **Journal of transport geography**, v.24, p. 471-482. 2012.

GEELS, F.W. Socio-technical transitions to sustainability: a review of criticisms and elaborations of the Multi-Level Perspective. **Current Opinion in Environmental Sustainability**, v. 39, p. 187-201. 2019.

GRANT, M. J.; BOOTH, A. A typology of reviews: an analysis of 14 review types and associated methodologies. **Health Information & Libraries Journal**, v.26, n.2, p. 91-108. 2009.

HAWKINS, T. R.; GAUSEN, O. M.; STRØMMAN, A. H. Environmental impacts of hybrid and electric vehicles—a review. **The International Journal of Life Cycle Assessment**, v.17, n.8, p. 997-1014. 2012.

HEKKERT, M.P. et al. Functions of innovation systems: A new approach for analysing technological change. **Technological forecasting and social change**, v.74, n.4, p. 413-432. 2007.

HEROLD, D. M.; LEE, K. H. Carbon management in the logistics and transportation sector: An overview and new research directions. **Carbon Management**, v.8, n.1, p. 79-97. 2017.

HLWIKI CANADA. **SCOPUS vs. Web of Science**. 2015. Available at: <http://hlwiki.slais.ubc.ca/index.php/Scopus_vs._Web_of_Science> Access on: 2 Feb. 2016.

HU, J.W.; CREUTZIG, F. A systematic review on shared mobility in China. **International Journal of Sustainable Transportation**, p. 1-16. 2021.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE. **Climate Change 2014:** Mitigation of Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

KLITKOU, A. et al. The role of lock-in mechanisms in transition processes: The case of energy for road transport. **Environmental Innovation and Societal Transitions**, v.16, p. 22-37. 2015.

KÖHLER, J. et al. An agenda for sustainability transitions research: State of the art and future directions. **Environmental Innovation and Societal Transitions**, v.31, p. 1-32. 2019.

KWAN, S. C.; HASHIM, J. H. A review on co-benefits of mass public transportation in climate change mitigation. **Sustainable Cities and Society**, v.22, p. 11-18. 2016.

LAGOUVARDOU, S.; PSARAFTIS, H. N.; ZIS, T. A literature survey on market-based measures for the decarbonization of shipping. **Sustainability**, v.12, n.10, p. 3953. 2020.

LI, J. Decoupling urban transport from GHG emissions in Indian cities—A critical review and perspectives. **Energy policy**, v.39, n.6, p. 3503-3514. 2011.

LOORBACH, D. Transition management for sustainable development: a prescriptive, complexity-based governance framework. **Governance**, v.23, n.1, p. 161-183. 2010.

MAGON, R.B. et al. Sustainability and performance in operations management research. **Journal of Cleaner Production**, v.190, p. 104-117. 2018.

MALERBA, F. Sectoral systems of innovation and production. **Research policy**, v.31, n.2, p. 247-264. 2002.

MARKARD, J.; HEKKERT, M.; JACOBSSON, S. The technological innovation systems framework: Response to six criticisms. **Environmental Innovation and Societal Transitions**, v. 16, p. 76-86. 2015.

MEREDITH, J. Theory building through conceptual methods. **International Journal of Operations & Production Management**. 1993.

MEYER, T. Decarbonizing road freight transportation–A bibliometric and network analysis. **Transportation Research Part D**: Transport and Environment, v.89, p. 102619. 2020.

MIOLA, A.; CIUFFO, B. Estimating air emissions from ships: Meta-analysis of modelling approaches and available data sources. **Atmospheric environment**, v. 45, n.13, p. 2242-2251. 2011.

MONGEON, P.; PAUL-HUS, A. The journal coverage of Web of Science and Scopus: a comparative analysis. **Scientometrics**, v. 106, n.1, p. 213-228. 2016.

MUÑOZ-VILLAMIZAR, A. et al. The environmental impact of fast shipping ecommerce in inbound logistics operations: A case study in Mexico. Journal of Cleaner Production, v.283, p.125400. 2021.

NEGRO, S.O.; SUURS, R.A.; HEKKERT, M.P. The bumpy road of biomass gasification in the Netherlands: Explaining the rise and fall of an emerging innovation system. **Technological forecasting and social change**, v.75, n.1, p. 57-77. 2008.

OGUNTONA, O. Longer-term aircraft fleet modelling: Narrative review of tools and measures for mitigating carbon emissions from aircraft fleet. **CEAS Aeronautical Journal**, v.11, n.1, p. 13-31. 2020.

O'MAHONY, T. State of the art in carbon taxes: a review of the global conclusions. **Green Finance**, v.2, n.4, p. 409-423. 2020.

PAGE M. J. et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. **Systematic Reviews 2021**, p. 10-89. 2021.

PILZ, T. et al. Systematic analysis of comparative studies between additive and conventional manufacturing focusing on the environmental performance of logistics operations. **Gestão & Produção**, v.27, n.3. 2020.

REQUIA, W. J. et al. How clean are electric vehicles? Evidence-based review of the effects of electric mobility on air pollutants, greenhouse gas emissions and human health. **Atmospheric Environment**, v.185, p. 64-77. 2018.

RIP, A.; KEMP, R. Technological change. **Human choice and climate change**, v.2, n.2, p. 327-399. 1998.

ROTMANS, J.; KEMP, R.; VAN ASSELT, M. More evolution than revolution: transition management in public policy. **Foresight**, v.3, n.1, p. 15-31. 2001.

SALVUCCI, R. et al. Energy scenario analysis for the Nordic transport sector: A critical review. **Energies**, v.12, n.12, p. 2232. 2019.

SCHOT, J.; GEELS, F.W. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. **Technology analysis & strategic management**, v.20, n. 5, p. 537-554. 2008.

SCHWANEN, T.; BANISTER, D.; ANABLE, J. Scientific research about climate change mitigation in transport: A critical review. **Transportation Research Part A:** Policy and Practice, v.45, n.10, p. 993-1006. 2011.

SEURING, S.; GOLD, S. Conducting content-analysis based literature reviews in supply chain management. **Supply Chain Management**, v.17, n.5, p. 544–555. 2012.

SEURING, S. et al. The application of theory in literature reviews – illustrated with examples from supply chain management. **International Journal of Operations & Production Management**, 2020.

SMIT, R.; NTZIACHRISTOS, L.; BOULTER, P. Validation of road vehicle and traffic emission models–A review and meta-analysis. **Atmospheric environment**, v.44, n.25, p. 2943-2953. 2010.

SMITH, A.; VOß, J.P.; GRIN, J. Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. **Research policy**, v.39, n.4, p. 435-448. 2010.

SOUSA, R.; VOSS, C.A. Contingency research in operations management practices. **Journal of Operations Management**, v.26, n.6, p. 697-713. 2008.

TAX FOUNDATION. **Carbon Taxes in Europe**. 2021. Available at: < https://taxfoundation.org/carbon-taxes-in-europe-2021/> Access on: 18 Aug. 2021.

THOMÉ, A. M. T.; SCAVARDA, L. F.; SCAVARDA, A. Conducting systematic literature review in operations management. **Prod. Plann. Control.**, v.27, n.5, p. 408–420. 2016.

VERNER, J. M. et al. Risks and risk mitigation in global software development: A tertiary study. **Information and Software Technology**, v.56, p. 54–78. 2014.

WALKER, H. et al. Theoretical perspectives in operations management: an analysis of the literature. **International Journal of Operations & Production Management**. 2015.

WEBER, K.M.; TRUFFER, B. Moving innovation systems research to the next level: towards an integratve agenda. **Oxford Review of Economic Policy**, v.33, n.1, p. 101-121. 2017.

WORLD HEALTH ORGANIZATION. Ambient (outdoor) air pollution. **World Health Organization**, 2018. World Health Organization Fact sheets. Available at: <https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health> Access on: 20 Jun. 2021

Appendices

Appendix 1 – Activity-based approach view controller

```
import UIKit

class ActivityBasedViewController: UIViewController,
UIPickerViewDelegate, UIPickerViewDataSource,
UITextFieldDelegate {

    @IBOutlet weak var transportModePicker: UIPickerView!
    @IBOutlet weak var transportVolumeTextField: UITextField!
    @IBOutlet weak var transportDistanceTextField: UITextField!
    @IBOutlet weak var emissionFactor: UITextField!

    var emissionsResults: Double?

    let transportModes:[(name: String, factor: Int)] = [("Road",
62), ("Rail", 22), ("Barge", 31), ("Short sea", 16),
("Intermodal road/rail", 26), ("Intermodal road/barge", 34),
("Intermodal road/short sea", 21), ("Pipelines", 5), ("Deep-sea
container", 8), ("Deep-sea tanker", 5), ("Air freight", 602)]

    override func viewDidLoad() {
        super.viewDidLoad()

        transportModePicker.delegate = self
        transportModePicker.dataSource = self
        transportVolumeTextField.delegate = self
        transportDistanceTextField.delegate = self
        emissionFactor.delegate = self

        transportVolumeTextField.keyboardType = .numberPad
        transportDistanceTextField.keyboardType = .numberPad
        emissionFactor.keyboardType = .numberPad

        let gesture = UITapGestureRecognizer(target: self,
action: #selector(self.someAction))
        self.view.addGestureRecognizer(gesture)

    }

    @objc
    func someAction(sender:UITapGestureRecognizer) {
        transportVolumeTextField.resignFirstResponder()
        transportDistanceTextField.resignFirstResponder()
        emissionFactor.resignFirstResponder()
    }

    func pickerView(_ pickerView: UIPickerView, didSelectRow
row: Int, inComponent component: Int) {

        emissionFactor.text = String(format: "%d",
transportModes[row].factor)

    }
```

```
    func pickerView(_ pickerView: UIPickerView, titleForRow row:
Int, forComponent component: Int) -> String? {
        return transportModes[row].name
    }

    func numberOfComponents(in pickerView: UIPickerView) -> Int
{
        return 1
    }

    func pickerView(_ pickerView: UIPickerView,
numberOfRowsInComponent component: Int) -> Int {
        return transportModes.count
    }

    func textFieldShouldReturn(_ textField: UITextField) -> Bool
{
        textField.resignFirstResponder()
    }

    @IBAction func calculateAction(_ sender: Any) {

        let selectedIndex =
transportModePicker.selectedRow(inComponent: 0)
        let volume = Double(transportVolumeTextField.text!) ??
0.0
        let distance = Double(transportDistanceTextField.text!)
?? 0.0
        let emissionFactor = Double(emissionFactor.text!) ?? 0.0

        emissionsResults = (volume * distance *
emissionFactor)/1000000

    }

    override func prepare(for segue: UIStoryboardSegue, sender:
Any?) {

        if let vc = segue.destination as? ResultsViewController
{

            vc.co2Emissions = emissionsResults
        }

    }

}
```

Appendix 2 – Energy-based approach view controller

```
import Foundation
import UIKit

class EnergyBasedViewController: UIViewController,
UIPickerViewDelegate, UIPickerViewDataSource,
UITextFieldDelegate {

    @IBOutlet weak var fuelTypePickerView: UIPickerView!
    @IBOutlet weak var unitSegmentedControl: UISegmentedControl!
    @IBOutlet weak var fuelConsumptionTextField: UITextField!
    @IBOutlet weak var emissionFactorTextField: UITextField!

    let fuelTypes:[(name: String, factor: Double, unit: Int)] =
[("Motor Gasoline", 2.8, 0), ("Diesel Oil", 2.9, 0), ("Gas Oil",
2.9, 0), ("Liquefied Petroleum Gas (LPG)", 1.9, 0), ("Compressed
Natural Gas (CNG)", 3.3, 1), ("Jet Kerosene", 3.5, 1),
("Residual Fuel Oil", 3.5, 1), ("Biogasoline", 1.8, 0),
("Biodiesel", 1.9, 0)]

    var selectedUnit: String?
    var emissionsResult: Double?

    override func viewDidLoad() {
        super.viewDidLoad()

        fuelTypePickerView.delegate = self
        fuelTypePickerView.dataSource = self
        fuelConsumptionTextField.delegate = self
        emissionFactorTextField.delegate = self

        fuelConsumptionTextField.keyboardType = .numberPad
        emissionFactorTextField.keyboardType = .numberPad

        let gesture = UITapGestureRecognizer(target: self,
action: #selector(self.someAction))
        self.view.addGestureRecognizer(gesture)

    }

    @objc

    func someAction(sender:UITapGestureRecognizer) {
        fuelConsumptionTextField.resignFirstResponder()
        emissionFactorTextField.resignFirstResponder()
    }

    func pickerView(_ pickerView: UIPickerView, didSelectRow
row: Int, inComponent component: Int) {
        emissionFactorTextField.text = String(format: "%.2f",
fuelTypes[row].factor)
        unitSegmentedControl.selectedSegmentIndex =
fuelTypes[row].unit
        unitChanged(self)

    }

    func pickerView(_ pickerView: UIPickerView, titleForRow row:
Int, forComponent component: Int) -> String? {
        return fuelTypes[row].name
```

```
    }

    func numberOfComponents(in pickerView: UIPickerView) -> Int
{
        return 1
    }

    func pickerView(_ pickerView: UIPickerView,
numberOfRowsInComponent component: Int) -> Int {
        return fuelTypes.count
    }

    @IBAction func unitChanged(_ sender: Any) {

        switch unitSegmentedControl.selectedSegmentIndex
        {
        case 0:
            selectedUnit = "Liters"
            fuelConsumptionTextField.placeholder = selectedUnit
            emissionFactorTextField.placeholder = "Kg CO2 per
liter fuel"
        case 1:
            selectedUnit = "Kg"
            fuelConsumptionTextField.placeholder = selectedUnit
            emissionFactorTextField.placeholder = "Kg CO2 per kg
fuel"
        default:
            break
        }

    }

    func textFieldShouldReturn(_ textField: UITextField) -> Bool
{
        textField.resignFirstResponder()
    }

    @IBAction func calculateAction(_ sender: Any) {

        let fuelConsumption =
Double(fuelConsumptionTextField.text!) ?? 0.0
        let emissionFactor =
Double(emissionFactorTextField.text!) ?? 0.0

        emissionsResult = (fuelConsumption *
emissionFactor)/1000

    }

    override func prepare(for segue: UIStoryboardSegue, sender:
Any?) {

        if let vc = segue.destination as? ResultsViewController
{

            vc.co2Emissions = emissionsResult
        }

    }

}
```

Appendix 3 – Results approach view controller

```
import Foundation
import UIKit

class ResultsViewController: UIViewController {

    @IBOutlet weak var co2EmissionsLabel: UILabel!

    var co2Emissions: Double?

    override func viewDidLoad() {
        super.viewDidLoad()

        co2EmissionsLabel.text = String(format: "%.2f", co2Emissions ?? 0.0)
```