FACTORS INFLUENCING THE CLIMATE-RELEVANT ENVIRONMENTAL IMPACT OF AIR TRANSPORT COMPARED TO RAIL AND ROAD TRANSPORT

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Abstract

In recent years, CO2 emissions have increasingly become the focus of science and industry. To achieve the goal of climate neutrality by 2050, all emitters must reduce their share. This includes the transport sector. To identify where these emissions in the transport sector originate and to draw conclusions on how to reduce them, it is necessary to examine the specific source of the emissions. The aim of this paper is to provide an overview of the different causes of emissions in air passenger transport compared to rail and road transport.

In addition, we examine how the emissions of different modes of transport are determined in the literature to date and what possibilities there are for determining the emissions from entire transport chains. The focus is on simulations to determine emissions over the life cycle of the infrastructure and the vehicle.

Keywords: CO2; emission; simulation, transport modes, literature review; climate relevance

1. Introduction

Under the Paris Agreement of 2015, it was decided to limit the global average temperature increase to below 2°C compared to pre-industrial levels. As a result, technology and science are increasingly focusing on understanding and reducing climate-relevant emissions. In 2022, the transport sector emitted approximately 7.97 billion tonnes of CO2, or about 20,6% of global carbon dioxid emissions.

This makes the transport sector the world's second largest emitter after the energy sector. [1] When broken down by transport mode, road transport accounts for the largest share at 79%. Air and rail account for 11% and 1% of global transport emissions in 2022. [2] Comparing emissions per passenger-kilometer from different modes of transport, domestic flights are the biggest emitters. [3]

In addition to the CO2 emitted during vehicle operation, there are other elements of a transport journey that must be added to the total emissions. Thereby, various factors such as the choice of engine, the speed at which the vehicle is driven, or the materials used influence emissions.

To understand the interdependencies and to be able to start reducing emissions at the relevant points, it is necessary to take a holistic view of the transport system on the route. Therefore, the only way is to consider the whole life cycle of the different components. In the following, the components relevant to the transport modes are identified, followed by the associated factors influencing emissions. This is followed by a summary of existing methods for quantifying the emissions of the components. The focus is on simulative approaches. The results of this work are based on a literature review and provide an overview of the current state of the art in the field of emission estimation in the transport sector.

2. Components and factors influencing carbon emissions

In the holistic consideration of CO2 emissions from transport modes, different elements and influencing factors can be considered. A life cycle assessment (LCA) includes the emissions caused by the production, operation, maintenance, and recycling of the elements. [4] Depending on the consideration and the objective of the analysis, different system boundaries can be drawn. The main elements and factors influencing CO2 emissions from infrastructure and vehicles are considered below.

2.1 Infrastructure

On the infrastructure side, the basic requirement is the respective track. In the case of rail transport, this is the track structures including e. g. rails and sleepers; in the case of road transport, it is the roads [5] which generate different levels of emissions depending on their length, construction method and materials used. In addition, both transport modes require their own structures including bridges, interchanges, tunnels. [5] These differ in material, length, and type. [6] In addition, the control infrastructure such as electrical equipment, signaling, telecommunications, level crossing signals and switching systems are required. [7] Further elements are the node infrastructure and additional buildings. In rail transport, this includes stations and stops as well as control centers and maintenance sheds. [6, 7] In road transport, this includes parking areas and buildings. Other buildings such as refueling, and service stations as well as road maintenance facilities are also required. In the case of buildings, the size, construction, and materials used influence emissions.

There is no physical infrastructure along the route in air transport. The only emissions along the route are those caused by the telecommunications equipment. At the start and end of the route, however, there are carbon emissions from airports and airfields as infrastructure nodes. The taxiway system and the apron are the central elements here, and their emissions vary according to their design, material, and size. Control infrastructure such as lighting and instrument landing systems are also necessary for operations as well as air traffic control and apron control. [8]

The production of energy for the operation, construction, maintenance, and recycling of the elements has an indirect impact. [9] The lifetime and capacity of the infrastructure elements must also be considered in the per capita consideration.

Other elements may be relevant depending on the route, the vehicle used, the area of application and the topography. Table 1 gives an overview of the different infrastructure elements and their impact on CO2 emissions depending on the mode of transport.

Tab. 1: Selection of infrastructure-related factors influencing CO2 emissions [5–9]]

Component (Influencing factors)	Road	Rail	Air
Track constructions (Length/ width, construction, materials, power consumption, energy source)	Roads, related equipment (e. g. vehicle restraint systems, embankment)	Rails, sleepers, related equipment (e. g. electrical equipment, railway crossing signals, switching systems)	Telecommunications equipment
Node Infrastructure (Size, construction, materials, power consumption, energy source)	Parking space	Stations, stopping points	Airport terminals, baggage handling systems
Constructions (Size, type, materials, power consumption, energy source)	Tunnels, bridges, interchanges	Tunnels, bridges, interchanges	Taxiway system, apron areas, related equipment (e. g. lighting; boarding, and loading equipment)
Control infrastructure (Power consumption, energy source)	Traffic lights, traffic signs	Signal boxes, signaling systems, switches	Air traffic control, related installations (e. g. radar, navigation beacon), apron control
Additional Buildings (Size, construction, materials, power consumption, energy source)	Petrol stations, service stations, road maintenance depots	Operating control points, maintenance sheds	maintenance sheds, hangars

2.2 Vehicle

On the vehicle side, there are other factors that influence CO2 emissions. During the production and recycling of the vehicle, emissions occur depending on its size, the materials used, the energy source used in production and the electricity consumption generated in the process.[8] This applies equally to all modes of transport and vehicles. Considering the capacity and service life of the vehicle, the emissions generated can be apportioned to the users.

In addition to the distance to be travelled, the following factors are particularly influential for the operation of the vehicle across **all modes of transport** [10–16]:

- Aerodynamics (shape and design, drag reduction)
- Weather conditions (temperature, wind, air pressure)
- Operating mass
- load factor
- Route characteristics (topography, curves, proportion of idling time)
- Propulsion (e. g. energy efficiency, fuel)
- Fuel characteristics (e. g. due to weather or availability)
- Maintenance and repair (e. g. maintenance intervals, effort, duration)

For **rail-bound transport**, the following factors are additionally relevant [11, 12, 17]:

- nonstop journey distance
- interior equipment (e. g. heating, ventilation, air-conditioning, lights)

In the operation of **road vehicles**, the following specific influencing factors [10, 15] can be mentioned:

- Auxiliary units (e. g. air conditioning, electric windows, parking aid)
- Driving behavior (e. g. maximum speed, acceleration, type of driving)
- Vehicle condition (e. g. timely oil change, checking tyre pressure and using the correct tyre type)
- Current traffic conditions (e. g. average speed, maximum speed, presence of traffic lights, congestion index)

In **aviation**, the additional influencing factors are as follows [8, 13, 14]:

- Cruising altitude
- Approach/ departure routes (e. g. angle of climb)
- Ground movements (e. g. taxiing)

3. Determination of carbon emissions

Based on the influencing factors outlined in Chapter 2, there are several ways to determine the emissions generated. Often the focus is on individual influencing factors, means, or modes of transport. Holistic approaches are rare due to their complexity.

To classify the methods used, it is important to first understand what legal requirements and regulations exist. Existing methods and studies are then analyzed in terms of their methodological approach and aim.

3.1 Regulations for determining carbon emissions

As an international guideline, the IPCC Guidelines for National Greenhouse Gas Inventories [16] form the basis for determining carbon emissions worldwide. As a United Nations institution, the Intergovernmental Panel on Climate Change (IPCC) regularly brings together experts from around the world to discuss and scientifically assess developments relating to climate change. [18]

The guidelines were published in 2006 and revised in 2019. They are divided into several volumes covering different areas of application. These include

- Volume 1: General Guidance and Reporting,
- Volume 2: Energy,
- Volume 3: Industrial Processes and Product Use,
- Volume 4: Agriculture, Forestry and Other Land Use, and
- Volume 5: Waste.

Volumes 1, 2 and 3 are particularly relevant to the transport sector. Volume 1 sets out the general guidelines and methodological approach. This forms the basis for the other volumes. Volume 2 covers emissions from energy use. It provides methodological approaches for calculating emissions and associated emission factors. Among other things, a distinction is made between stationary combustion and mobile combustion. For fuel combustion activities, transport is a sub-item, and the relevant content can be found in the chapters on civil aviation, road transport and railways. Stationary combustion includes information on emissions from energy use in construction, which includes the construction of transport infrastructure and vehicles. The mobile combustion chapter presents approaches to determining carbon emissions from energy use for operating the different types of vehicles in each of the above modes. In both chapters decision trees are used to determine which of the given approaches should be chosen for the determination. Data availability in general, availability of specific national data, specification and verification options as well as level of detail are considered. Volume 3 deals with carbon emissions from industrial processes such as the manufacture of goods and use of resources. Approaches and emission factors for different materials from the mineral, chemical and metal industries are presented.

The international guidelines are implemented within countries through national inventory reports. These are closely aligned with the IPCC guidelines and are therefore similar in structure (e.g. National Inventory Report for the German Greenhouse Gas Inventory [19]).

3.2 Methods for determining carbon emissions

Carbon emissions can be determined either analytically or simulatively. In both cases, the above guidelines can be followed, and the recommended equations and emission factors can be stored. Each method can offer advantages depending on the question and the component under consideration. Simulative approaches are mainly divided into system-dynamic, discrete-event and agent-based modelling. Depending on the application, each approach may have different advantages. System dynamics is the simulation method with the highest level of abstraction. It uses stock and flow diagrams and feedback loops to understand causal relationships. System dynamics is often used for social, economic and strategic issues. Discrete event simulation is used for low to medium level questions. Here, passive entities move through blocks of flowcharts, where they are delayed, must wait and are processed according to the capacity of the block. All levels of abstraction can be covered in agent-based simulation. At the heart of the model are the agents, to which individual behaviors are assigned and which can interact with each other. [20]

Irrespective of the method of determination, LCA is often chosen as the basis for studies dealing with the determination of carbon emissions. (see section 2). LCA is used to assess the potential environmental impact of a product system over its entire life cycle. It is divided into four steps: definition of the objective and scope, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of the results. [4] In the context of this study, the quantification of CO2 emissions in the life cycle is considered. Depending on the objective of the LCA, the above-mentioned components and their influencing factors can be considered for the transport modes (see section 2.1 and 2.2).

The idea of combining simulation and LCA has been taken up in the literature for a variety of issues. The search shows that search terms for the combination of system dynamic models and LCA generate a significantly higher number of hits than LCA with the other simulation methods. McAvoy et al. show in their review that the consideration of temporal dynamics and the use of system dynamic models for LCA has added value. This approach has already been used for several applications, such as electric vehicles, and shows both qualitative and quantitative results, as cause and effect are also investigated. [21] Yu et al. also show that the inclusion of system dynamics, time scale and system interaction mechanisms can improve LCA, while LCA extends the scope of system dynamics modelling, thus exploiting the complementary advantages of both approaches. [22] Davis et al. have integrated a simplified LCA into an agent-based model that provides environmental information about an energy infrastructure system. [23]

There are already several studies in the literature, which differ in terms of methodology and scope. Various studies for entire modes of transport, individual vehicles or infrastructures are analyzed and briefly summarized below. In line with the previous structure of the study, a distinction is again made between infrastructure and vehicle.

<u>Infrastructure</u>

In the field of methods for determining infrastructure carbon emissions, there are many studies that approach the problem analytically. For road transport, these include the study by Keijzer et al. [24]. This study examines the carbon emissions of different materials and techniques used in the construction and maintenance of road infrastructure in the Netherlands. Han et al. carry out a similar study based on four different scenarios with a calculation model for China. [25] Miliutenko is also investigating the life cycle impacts of road infrastructure, using a road tunnel and asphalt recycling as examples. [26] Müller et al. also showed the importance of infrastructure-related emissions in their study. [27] This is also confirmed by Fridel et al. in the context of an analysis, but of freight transport for all modes. They carry out an LCA and use existing data for their analytical study. [28] For example, Saxe et al. carried out a study for the railways. They take into account emissions from construction, operation and maintenance. [29] In a literature review, Pritchard and Preston examine the influence of tunnels on infrastructure emissions and vehicle operation. [30] Kaewunruen et al. also confirm that rail infrastructure is a major source of emissions. In particular, compared to other modes of transport, the share of emissions caused by infrastructure is higher. [31] In the field of aviation, Nagendra shows that the consideration of infrastructure is also a relevant issue for airport operations. The aim of the study is to evaluate the determination of an international airport's emissions inventory and the level of carbon emissions from these sources, and to define measurement requirements. [32] Xiong et al. also looked at emissions from airport operations and concluded that they have a significant impact. [33] Postorino et al. have developed a model that identifies the contribution of different emission sources in airport operations and classifies their share of total emissions. [34] Cui et al. develop a methodology to measure the environmental performance of Chinese airlines by using neural networks to analyze the impact of various airport infrastructure features on environmental performance. The focus is on the reduction of carbon emissions. [35] In 2013, the German Federal Environment Agency also published a study [8] on the use of material flow analysis to determine the greenhouse gas emissions caused by the construction, maintenance and operation of infrastructure as well as the manufacture and maintenance of vehicles for road, rail, air and inland waterway transport.

Recent simulation studies that consider the transport infrastructure as a whole and not just the materials used, or individual components are rarely the focus of scientific research. Infrastructure operation is partially considered, but construction and recycling are largely neglected. These may need to be combined through separate studies of buildings [36] and infrastructure materials [37]. Oumer et al. have developed an energy efficiency model based on discrete event simulation to reduce CO2 emissions in vehicle assembly plants. [38] In addition to its relevance to vehicle design, this provides an opportunity to quantify the energy consumption of infrastructure. A study by Hu et al. looks at emissions from the construction of railway infrastructure. A literature review is used to identify relevant emission factors, expert interviews are used to derive limits, and a model is developed for the production phase of construction materials, the transport phase of construction materials, and the construction phase of railway infrastructure. [39] Gonzalez et al. show that the use of discrete event simulation offers advantages regarding the operation of road infrastructure and, in particular, road construction operations. In order not to consider the frequently changing influencing factors exclusively statically, a simulation study is carried out here for the consideration of fugitive emissions and exhaust gases caused by production and traffic conditions. [40]

Vehicle

For vehicle emissions, several LCA studies exist. Many of the studies take an analytical approach, e. g. in the aviation sector by Montlaur [41]. In addition, there are many studies, such as [42–46], which allow conclusions to be drawn about the resulting carbon emissions by modelling interventions in traffic flow, transport demand or modal split. Other existing studies primarily use methods for individual transport modes on specific routes or for the total transport performance of a specific region, e. g. [47] by Guo et al. with determining carbon emissions für the Chinese passenger vehicle sector with an system dynamics approach.

In this study, however, we focus on the studies that concentrate on the determination of emissions using simulation approaches. Simulative studies that deal with the emissions of vehicles over their life cycle are summarised in Tab. 2. Although simulation studies dealing with the carbon emissions of vehicles and focusing on the life cycle of the vehicle are more common than the same studies for infrastructure, simulation studies are less frequently used than analytical studies for vehicle.

Tab. 2: Selection of simulative studies to determine the carbon emissions of vehicles

Author	Rahn et al.	Kickhäfer et al.	Nalbur et al.	Onat et al.
Year	2022	2018	2024	2016
Reference	[48]	[49]	[50]	[51]
Transport mode	Air	Air	Road	Road
Vehicle	Airbus A320	Aircraft fleet	Electric buses	Electric Vehicles
Method	Discrete Event Simulation	System Dynamics	System Dynamics, Discrete Event Simulation	System Dynamics
Aim	Carbon emission while life cycle	the extent to which alternative fuels can contribute to the reduction targets	Impact of green logistics activities	Quantitative assessment of sustainability over the entire life cycle

These studies show that modelling can be used as an approach to LCA. Discrete event simulation can add value, particularly in relation to vehicle maintenance cycles. System dynamic modelling offers advantages due to the possibility to analyze and map complex interdependencies, especially for overall transport issues. However, they can also be used for LCA of vehicles.

Additionally, System dynamic simulation is already used in the field of freight transport, for example in the studies of Cao et al. [52] and Huang et al. [53]. Cao et al. simulate the reduction of carbon emissions in green electric-coal supply chains. Huang et al. deals with the reduction of carbon emissions in freight transport on road and rail in general. For entire passenger transport chains, the literature review showed that there are no simulative studies on the life cycle and the resulting carbon emissions.

4. Conclusion and Outlook

The first part of the study identifies the various factors influencing carbon emissions over the life cycle of infrastructure and vehicles. It shows that these are multi-layered and that a very important issue in integrating the elements into carbon assessment methodologies is the definition of an appropriate model boundary. The choice of model boundary is a critical factor in the comparability of these studies, especially if traffic volumes in different studies are to be compared.

The literature review also shows that there are several analytical and simulative studies on the carbon emissions of infrastructure elements and vehicles. The number of analytical models clearly exceeds the number of simulative models. This is partly due to the cost and complexity of such models. At the same time, as noted above, simulation can offer many advantages in terms of identifying causal relationships, integrating variables that change over time, and combining qualitative and quantitative results. In simulation studies, the focus of the simulation within the studies is usually on describing the environment or its change, and is less often used to calculate carbon emissions per se. However, some models show that this is possible and has advantages.

Surprisingly, there are very few LCA studies of infrastructure that take a holistic view of a mode of transport over its entire life cycle, as this would make sense due to the possibility of changing the variables over time.

Furthermore, there are only few studies that combine simulation methods and use a multi-method simulation approach, although this is a possible and promising approach. [20]

In the future, based on existing studies, it may be possible to monitor the lifecycles of entire transport systems and assess their environmental impact at a macroscopic level by using a multi-method simulation approach.

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6. Copyright Statement

References

[1] EDGAR/JRC, *Global carbon dioxide emissions from 1970 to 2022, by sector (in million metric tons of carbon dioxide) Chart*.

[2] IEA, *Distribution of carbon dioxide emissions produced by the transportation sector worldwide in 2022, by sub sector*.

[3] OWID, *Carbon footprint of select modes of transport per kilometer of travel in 2018 (in grams of carbon dioxide equivalent per passenger kilometer)*.

[4] Deutsches Institut für Normung, *DIN EN ISO 14040, Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen (ISO 14040:2006 + Amd 1:2020): = Environmental management - life cycle assessment - principles and framework (ISO 14040:2006 + Amd 1:2020) = Management environnemental - analyse du cycle de vie - principes et cadre (ISO 14040:2006 + Amd 1:2020),* 14040th ed. Berlin: Beuth Verlag GmbH, 2021.

[5] Z. Dvořák, E. Sventeková, D. Řehák, and Z. Čekerevac, "Assessment of Critical Infrastructure Elements in Transport," *Procedia Engineering*, vol. 187, pp. 548–555, 2017, doi: 10.1016/j.proeng.2017.04.413.

[6] B. Leitner, L. Môcová, and M. Hromada, "A New Approach to Identification of Critical Elements in Railway Infrastructure," *Procedia Engineering*, vol. 187, pp. 143–149, 2017, doi: 10.1016/j.proeng.2017.04.360.

[7] D. Rehak, S. Slivkova, R. Pittner, and Z. Dvorak, "Integral approach to assessing the criticality of railway infrastructure elements," *International Journal of Critical Infrastructures*, vol. 16, no. 2, pp. 107–129, 2020. [Online]. Available: https://ideas.repec.org/a/ids/ijcist/v16y2020i2p107-129.html

[8] M. Mottschall and T. Bergmann, *Treibhausgas-Emissionen durch Infrastruktur und Fahrzeuge des Straßen-, Schienen- und Luftverkehrs sowie der Binnenschifffahrt in Deutschland: Arbeitspaket 4 des Projektes "Weiterentwicklung des Analyseinstrumentes Renewbility"*, 2013.

[9] K. JONSSON, "Indirect energy associated with Swedish road transport," *EJTI*, no. 7, 2007.

[10] W. Li, P. Stanula, P. Egede, S. Kara, and C. Herrmann, "Determining the Main Factors Influencing the Energy Consumption of Electric Vehicles in the Usage Phase," *Procedia CIRP*, vol. 48, pp. 352–357, 2016, doi: 10.1016/j.procir.2016.03.014.

[11] M. Janić, "Estimation of direct energy consumption and CO 2 emission by high speed rail, transrapid maglev and hyperloop passenger transport systems," *International Journal of Sustainable Transportation*, vol. 15, no. 9, pp. 696–717, 2021, doi: 10.1080/15568318.2020.1789780.

[12] Y.-Z. Wang, S. Zhou, and X.-M. Ou, "Development and application of a life cycle energy consumption and CO2 emissions analysis model for high-speed railway transport in China," *Advances in Climate Change Research*, vol. 12, no. 2, pp. 270–280, 2021, doi: 10.1016/j.accre.2021.02.001.

[13] M. Grote, I. Williams, and J. Preston, "Direct carbon dioxide emissions from civil aircraft," *Atmospheric Environment*, vol. 95, pp. 214–224, 2014, doi: 10.1016/j.atmosenv.2014.06.042.

[14] M. N. Postorino, L. Mantecchini, and F. Paganelli, "Improving taxi-out operations at city airports to reduce CO2 emissions," *Transport Policy*, vol. 80, pp. 167–176, 2019, doi: 10.1016/j.tranpol.2018.09.002.

[15] European Commission. Joint Research Centre., *Review of in use factors affecting the fuel consumption and CO2 emissions of passenger cars*: Publications Office, 2016.

[16] H. S. Eggleston, Ed., *2006 IPCC guidelines for national greenhouse gas inventories*. Hayama, Japan: Institute for Global Environmental Strategies, 2006.

[17] M. Ćwil, W. Bartnik, and S. Jarzębowski, "Railway Vehicle Energy Efficiency as a Key Factor in Creating Sustainable Transportation Systems," *Energies*, vol. 14, no. 16, p. 5211, 2021, doi: 10.3390/en14165211.

[18] Deutsche IPCC-Koordinierungsstelle, *Der IPCC: Zwischenstaatlicher Ausschuss für Klimaänderungen.* [Online]. Available: https://www.de-ipcc.de/119.php (accessed: Jun. 13 2024).

[19] German Environment Agency, *National Inventory Report for the German Greenhouse Gas Inventory 1990 – 2021*, 2023.

[20] A. Borshchev, *The big book of simulation modeling: Multimethod modeling with AnyLogic 6*. Chicago: AnyLogic North America, 2013.

[21] S. McAvoy, T. Grant, C. Smith, and P. Bontinck, "Combining Life Cycle Assessment and System Dynamics to improve impact assessment: A systematic review," *Journal of Cleaner Production*,

vol. 315, p. 128060, 2021, doi: 10.1016/j.jclepro.2021.128060.
[22] F. Yu *et al.,* "Assessment of system sustainability: a critical review of the combined application of system dynamics and life cycle assessment," *Energ. Ecol. Environ.*, vol. 9, no. 1, pp. 58–67, 2024, doi: 10.1007/s40974-023-00313-5.
[23] C. Davis, I. Nikolić, and G. P. J. Dijkema, "Integration of Life Cycle Assessment Into Agent-Based Modeling," *J of Industrial Ecology*, vol. 13, no. 2, pp. 306–325, 2009, doi: 10.1111/j.1530-9290.2009.00122.x.
[24] E. E. Keijzer, G. A. Leegwater, S. E. de Vos-Effting, and M. S. de Wit, "Carbon footprint comparison of innovative techniques in the construction and maintenance of road infrastructure in The Netherlands," *Environmental Science & Policy*, vol. 54, pp. 218–225, 2015, doi: 10.1016/j.envsci.2015.06.010.
[25] Y. Han *et al.,* "Life cycle carbon emissions from road infrastructure in China: A region-level analysis," *Transportation Research Part D: Transport and Environment*, vol. 115, p. 103581, 2023, doi: 10.1016/j.trd.2022.103581.
[26] S. Miliutenko, *Life cycle impacts of road infrastructure: Assessment of energy use and greenhouse gas emissions*. Stockholm: Architecture and the Built Environment, KTH Royal Institute of Technology, 2012.
[27] D. B. Müller *et al.,* "Carbon emissions of infrastructure development," *Environmental science & technology*, vol. 47, no. 20, pp. 11739–11746, 2013, doi: 10.1021/es402618m.
[28] E. Fridell, S. Bäckström, and H. Stripple, "Considering infrastructure when calculating emissions for freight transportation," *Transportation Research Part D: Transport and Environment*, vol. 69, pp. 346–363, 2019, doi: 10.1016/j.trd.2019.02.013.
[29] S. Saxe, G. Casey, P. Guthrie, K. Soga, and H. Cruickshank, "Greenhouse gas considerations in rail infrastructure in the UK," *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, vol. 169, no. 5, pp. 171–180, 2016, doi: 10.1680/jensu.15.00015.
[30] J. A. Pritchard and J. Preston, "Understanding the contribution of tunnels to the overall energy consumption of and carbon emissions from a railway," *Transportation Research Part D: Transport and Environment*, vol. 65, pp. 551–563, 2018, doi: 10.1016/j.trd.2018.09.010.
[31] S. Kaewunruen, J. M. Sussman, and H. H. Einstein, "Strategic framework to achieve carbon-efficient construction and maintenance of railway infrastructure systems," *Front. Environ. Sci.*, vol. 3, p. 123473, 2015, doi: 10.3389/fenvs.2015.00006.
[32] S. M. Shiva Nagendra, Ed., *Urban Air Quality Monitoring, Modelling and Human Exposure Assessment*. Singapore: Springer Singapore Pte. Limited, 2021.
[33] X. Xiong, X. Song, A. Kaygorodova, X. Ding, L. Guo, and J. Huang, "Aviation and carbon emissions: Evidence from airport operations," *Journal of Air Transport Management*, vol. 109, p. 102383, 2023, doi: 10.1016/j.jairtraman.2023.102383.
[34] M. N. Postorino and L. Mantecchini, "A transport carbon footprint methodology to assess airport carbon emissions," *Journal of Air Transport Management*, vol. 37, pp. 76–86, 2014, doi: 10.1016/j.jairtraman.2014.03.001.
[35] Q. Cui, J. Antunes, P. Wanke, Y. Tan, D. Roubaud, and C. J. C. Jabbour, "The impact of Chinese airport infrastructure on airline pollutant emissions: A hybrid stochastic-neural network approach based on utility functions," *Journal of Environmental Management*, vol. 352, p. 120117, 2024, doi: 10.1016/j.jenvman.2024.120117.
[36] L. F. Cabeza, L. Rincón, V. Vilariño, G. Pérez, and A. Castell, "Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review," *Renewable and Sustainable Energy Reviews*, vol. 29, C, pp. 394–416, 2014. [Online]. Available: https://ideas.repec.org/a/eee/rensus/v29y2014icp394-416.html
[37] B. Yu, S. Wang, X. Gu, F. Ni, and Q. Liu, "Environmental burden evaluation of hot in-place recycling of asphalt pavement based on discrete event simulation," *Transportation Research Part D: Transport and Environment*, vol. 65, pp. 151–160, 2018, doi: 10.1016/j.trd.2018.08.012.
[38] A. Oumer, S. M. Atnaw, J. K. Cheng, and L. Singh, "Improving Energy Efficiency for the Vehicle Assembly Industry: A Discrete Event Simulation Approach," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 160, p. 12069, 2016, doi: 10.1088/1757-899X/160/1/012069.
[39] X. Hu, X. Zhang, L. Dong, H. Li, Z. He, and H. Chen, "Carbon Emission Factors Identification and Measurement Model Construction for Railway Construction Projects," *International journal of environmental research and public health*, vol. 19, no. 18, 2022, doi: 10.3390/ijerph191811379.
[40] V. González and T. Echaveguren, "Exploring the environmental modeling of road construction operations using discrete-event simulation," *Automation in Construction*, vol. 24, pp. 100–110,

2012, doi: 10.1016/j.autcon.2012.02.011.
[41] A. Montlaur, L. Delgado, and C. Trapote-Barreira, "Analytical Models for CO2 Emissions and Travel Time for Short-to-Medium-Haul Flights Considering Available Seats," *Sustainability*, vol. 13, no. 18, p. 10401, 2021, doi: 10.3390/su131810401.
[42] A. M. Syré, F. Heining, and D. Göhlich, "Method for a Multi-Vehicle, Simulation-Based Life Cycle Assessment and Application to Berlin's Motorized Individual Transport," *Sustainability*, vol. 12, no. 18, p. 7302, 2020, doi: 10.3390/su12187302.
[43] C. Linton, S. Grant-Muller, and W. F. Gale, "Approaches and Techniques for Modelling CO 2 Emissions from Road Transport," *Transport Reviews*, vol. 35, no. 4, pp. 533–553, 2015, doi: 10.1080/01441647.2015.1030004.
[44] Y. Huang, R. Bird, and M. Bell, "A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation," *Transportation Research Part D: Transport and Environment*, vol. 14, no. 3, pp. 197–204, 2009, doi: 10.1016/j.trd.2008.12.003.
[45] A. Pukhova, A. T. Moreno, C. Llorca, W.-C. Huang, and R. Moeckel, "Agent-Based Simulation of Long-Distance Travel: Strategies to Reduce CO2 Emissions from Passenger Aviation," *UP*, vol. 6, no. 2, pp. 271–284, 2021, doi: 10.17645/up.v6i2.4021.
[46] X. Liu, S. Ma, J. Tian, N. Jia, and G. Li, "A system dynamics approach to scenario analysis for urban passenger transport energy consumption and CO2 emissions: A case study of Beijing," *Energy policy*, vol. 85, pp. 253–270, 2015, doi: 10.1016/j.enpol.2015.06.007.
[47] Z. Guo, T. Li, S. Peng, X. Wang, and H. Zhang, "When will China's passenger vehicle sector reach CO2 emissions peak? A life cycle approach based on system dynamics," *Sustainable Production and Consumption*, vol. 33, pp. 508–519, 2022, doi: 10.1016/j.spc.2022.07.025.
[48] A. Rahn, K. Wicke, and G. Wende, "Using Discrete-Event Simulation for a Holistic Aircraft Life Cycle Assessment," *Sustainability*, vol. 14, no. 17, p. 10598, 2022, doi: 10.3390/su141710598.
[49] K. Kieckhäfer, G. Quante, C. Müller, T. Spengler, M. Lossau, and W. Jonas, "Simulation-Based Analysis of the Potential of Alternative Fuels towards Reducing CO2 Emissions from Aviation," *Energies*, vol. 11, no. 1, p. 186, 2018, doi: 10.3390/en11010186.
[50] B. E. Nalbur and O. Yavas, "System dynamics model and discrete-event simulation of green logistics cases for the electric bus industries," *IJGW*, vol. 32, no. 2, pp. 148–159, 2024, doi: 10.1504/IJGW.2024.135989.
[51] N. C. Onat, M. Kucukvar, O. Tatari, and G. Egilmez, "Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: a case for electric vehicles," *Int J Life Cycle Assess*, vol. 21, no. 7, pp. 1009–1034, 2016, doi: 10.1007/s11367-016-1070-4.
[52] Y. Cao *et al.,* "System dynamics simulation for CO2 emission mitigation in green electric-coal supply chain," *Journal of Cleaner Production*, vol. 232, pp. 759–773, 2019, doi: 10.1016/j.jclepro.2019.06.029.
[53] Da Huang, M. Han, and Y. Jiang, "Research on Freight Transportation Carbon Emission Reduction Based on System Dynamics," *Applied Sciences*, vol. 11, no. 5, p. 2041, 2021, doi: 10.3390/app11052041.