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Simulation-based Assessment of Sustainability Metrics in the Transportation Domain: A Systematic Literature Review

Simulationsbasierte Bewertung von Nachhaltigkeitskriterien im Transportbereich: Eine systematische Literaturrecherche

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Abstract: Transportation is crucial for economic prosperity and the quality of life. Yet, it is also associated with negative externalities (e.g. emissions). Developing and implementing more sustainable means of transportation is one of the major concerns of researchers and policy-makers to improve liveability and contribute to environmental conservation. The use of simulation to evaluate sustainability-related indicators of transportation systems has received increasing attention within the last decades. However, research and practice still lack a comprehensive overview of common performance indicators for different transportation modes that are particularly suitable to be analysed by means of simulation-based research. Therefore, we employ a systematic literature review to delineate and conceptualize the status quo of simulation-based sustainability research in the transportation sector. We provide insights on the appropriateness of different simulation methodologies and tools for various transportation modes and sustainability measures and identify research trends and knowledge gaps to provide guidance for prospective simulation-based research.

1 Introduction

As transportation of passengers and freight is one of the primary sources of negative externalities such as environmental emissions, noise and traffic accidents, it is a major concern in the pursuit of sustainability (Menendez and Ambühl 2022). More sustainable transportation systems yield the potential to improve people's quality of life, while at the same time contributing to environmental conservation and creating opportunities for economic growth (Menendez and Ambühl 2022). The main objective in this context is to invent novel or adapt existing transportation systems that are capable of reducing environmental damages (e.g., by emissions), social fallouts (e.g., noise, safety), and operational costs (e.g., profitability) (Mikušová et al. 2021).

As transportation systems are highly complex and show a large degree of non-linear interdependencies and system components, simulation has become a popular approach to analyse these systems (Auf der Landwehr et al. 2020; Sayyadi and Awasthi 2018). Furthermore, simulation methods are frequently used in transportation contexts as they help to conceptualize and mimic systems with highly intricate interrelationships, various design variants, and operational properties that have not yet been piloted in practice (Wenzel 2018). Therefore, computer simulation and traffic modelling approaches are increasingly used by scholars to investigate the sustainability-related impacts of different transportation systems (Mikušová et al. 2021). The use of simulation to assess sustainability-related impacts caused by a transportation system requires indicators that measure the response of the system with respect to objectives under certain conditions (Sayyadi and Awasthi 2018). In accordance to Sayyadi and Awasthi (2018), such indicators should be measurable, goal oriented, understandable, precise and not multifaceted. Nevertheless, due to the wide range of involved areas, uncertainty and not explicitly defined objectives indicators strongly vary within the literature, which is mainly due to different levels of interest, expertise and knowledge of the involved authors or organizations (Sayyadi and Awasthi 2018).

The global increase of traffic and transportation volume and the growing intention to mitigate its negative effects has led to a large number of simulation studies answering transport- and sustainability-related questions (Menendez and Ambühl 2022; Mikušová et al. 2021). However, current research lacks a comprehensive review of common and relevant key performance indicators for different transportation modes that are particularly suitable to be analysed by means of simulation-based research. Moreover, it is not yet clear in how far the assessment of a given performance metric is contingent on the investigated transportation mode as well as the adopted simulation methodology and software, or vice versa. Therefore, we opt to provide a sound overview on the status quo and interferences of simulation-based research for the assessment of environmental, social, and economic performance indicators within the transportation domain to foster a more holistic understanding of how simulation-based research approaches can be employed to evaluate sustainability in this sector.

For that purpose, we apply a systematic literature review that analyses simulation studies in the context of transportation. In doing so, we address the following research question:

RQ: What simulation-based research approaches can be applied to assess different sustainability indicators in the generic realms of transportation?

2 Theoretical Background

Sustainability is a multifarious concept that relates to three dimensions, namely economy, environment, and society (Litman and Burwell 2006). In the light of trends such as global warming, growing population and exhausted resources, sustainability is a major concern of our time. Especially the transportation sector is in focus of the scientific debate as it is characterized by economic inefficiency, high amounts of environmental pollution and its socially detrimental effects (Menendez and Ambühl 2022). In this context, various indicators are used to assess economic, social, and ecological performance (Sayyadi and Awasthi 2018).

Frequently used economic measures in the context of transportation are monetary costs, profit, revenue, market share, and product quality (e.g., Tan et al. 2009). Measurements such as fleet size, mileage, utilization, standing time, trip counts, or travel time (e.g. lead times) are also commonly used (e.g., Bae et al. 2022; Linares et al. 2017). While indicators such as energy consumption or waste (e.g., Waisman et al. 2013) are typically associated with environmental sustainability, they also play a role in terms of economic performance as they refer to inefficiencies (e.g., Burinskiene et al. 2018). In order to measure the environmental impacts of transportation, several studies use the indicator GHG emissions (e.g. Fan et al. 2021). Nevertheless, many studies apply more specific measures such as emissions of CO, CO_2, NO_x, PM, ozone pollution (e.g., Basaric et al., 2015; Stark et al. 2018). Besides its impact on air quality, transportation may also influence the environment due to noise and soil pollution (e.g., Stark et al. 2018). Some studies use mileage or modal split (e.g. the share of private motorized transport) as indicators as both are related to detrimental environmental effects (e.g., Waisman et al. 2013). Nevertheless, as modal split directly refers to people's choice to use a transportation system, it is also typically used to assess social sustainability (e.g., Ben-Dor et al. 2022). Similarly, while costs are usually related to monetary benchmarks of operators they may also refer to societal costs (e.g. due to unemployment) (Hu et al. 2020). Other frequently used social indicators are utilization (e.g. the frequency a service is used), accessibility, acceptance, traffic density, travel time, waiting time, and service (e.g., Linares et al. 2017; Fan et al. 2021; Tan et al. 2009). Noise levels caused by transport operations and people's safety can also be found in literature (e.g., Basaric et al. 2015). Due to the emergence of intelligent transportation systems, the measurement of safety not only refers to people's health but also to the privacy of communication flows (Hatzivasilis et al. 2020).

Due to the complex nature of transportation systems, computer simulation and traffic modelling approaches are frequently used to assess their sustainability-related impacts (Mikušová et al. 2021). Using agent-based simulation, Bae et al. (2022) investigate the potential for collaborative planning of a system in urban areas that acts as a freight transport hub with several e-commerce warehouses. They assess the sustainability-related impact of the system using indicators such as mileage, lead times, and utilization. In order to assess the impact of shared autonomous vehicle introduction into the metropolitan area of Jerusalem, Ben-Dor et al. (2022) applied an agent-based simulation modeled in MATSim. They examined the effects of this novel transportation scheme on the existing equilibrium between public transport and private cars using indicators such as modal split or travel time. Tomás et al. (2021) analysed the impacts of carpooling implementation into different university campus networks considering COVID-19 safety measures. Modelling a microscopic traffic simulation, they assess the impacts of carpooling regarding traffic density, mileage, and travel time as well as in terms of different vehicular exhaust emissions.

Few literature reviews exist that provide orientation in the broad field of sustainable transportation. La Torre et al. (2021) review existing work on scientific methodologies used to promote sustainable transportation systems, including simulation and optimization models as well as machine learning and fuzzy sets. Additionally, they provide a classification of challenges, best practices, future trends, and research gaps.

A review conducted by Muller et al. (2021) aims to identify available methodologies for assessing the sustainability impact of potential mobility as a service (MaaS) implementations from a whole system perspective. They provide information about simulation tools and models, relative to their ability to support transportation planners, to holistically assess the MaaS concept, at a city level.

3 Methodology

To address our research question, we followed the rigorous guidelines of Webster and Watson (2002). Following Leidner (2018), the literature review can be classified as 'assessing review' and opts to synthesize existing knowledge on the simulation-based assessment of sustainability-related performance indicators in the transportation sector to provide a thorough overview of trends and research gaps. The actual review process consists of multiple phases, namely: (1) database and journal selection, (2) literature search with filtering, (3) backward (i.e., assessing citations from the literature results) and forward (i.e., identifying articles that quote relevant publications discerned during the keyword search) search as well as (4) classification based on performance indicators for measuring sustainability, simulation technique, simulation-software, transport mode, and determinant (Webster and Watson 2002).

During our review, we considered more than 700 publications from different research disciplines, focusing mainly, but not exclusively, on simulation-, sustainability-, and transport-related conferences and journals. Our search results predominantly stem from a keyword search that has been conducted in Scopus between January and April 2023 for the fields abstract, title, and keywords applying the following search string:

("simulat" AND "transport*" AND "sustainab*" AND ("mobility" OR "logistic*"))*

After excluding duplicates and non-English publications, we obtained a set of 663 papers. Subsequently, the first and second author of this paper independently read the abstract, introduction and results of each article and determined its relevance by assessing whether a publication applies simulation methods in order to assess sustainability indicators in the field of transportation. Ultimately, we identified 339 relevant publications applying various simulation techniques and software to transport and sustainability related questions. All relevant papers were subsequently analysed regarding sustainability indicators, simulation techniques, simulation software, and determinants (e.g. policies whose impacts were measured) used and coded. Afterwards, the coding was reviewed by the authors. In case of discordances or disagreements, the authors discussed their opinions to reach a joint verdict about the in- or exclusion as well as individual coding of a given publication.

4 Results

Out of the 339 publications that we analysed in the course of our literature review, 109 articles have been published in conference proceedings of peer-reviewed conferences such as the *Winter Simulation Conference*, while 230 papers have been publicised in scientific journals such as the *Journal of Computational Science*. As depicted in Table 1, a variety of metrics related to social, economic, and environmental sustainability has been investigated by simulation-based research over the last decades.

Table 1: Sustainability metrics investigated in simulation-based research

Social sustainab.		Economic sustainab.		Environmental sustainab.	
Metric	Count (%)	Metric	Count (%)	Metric	Count (%)
Travel time	85 (28.6)	Costs	115 (39.7)	CO2 emiss.	101 (21.8)
Traffic density	76 (25.6)	Utilization	38 (13.1)	Energy cons.	95 (20.5)
Waiting time	34 (11.4)	Travel time	32 (11.0)	Other emiss.*	65 (14.0)
Safety (Health)	25 (8.4)	Mileage	23 (7.9)	Mileage	46 (9.9)
Modal split	20 (6.7)	Energy cons.	21 (7.2)	NOx emiss.	44 (9.5)
Service	20 (6.7)	Revenue	17 (5.9)	PM emiss.	38 (8.2)
Accessibility	15 (5.1)	Fleet size	13 (4.5)	CO emiss.	30 (6.5)
Utilization	6 (2.0)	Market share	13 (4.5)	GHG emiss.	26 (5.6)
Acceptance	5 (1.7)	Profit	5 (1.7)	Noise	7 (1.5)
Costs	5 (1.7)	Standing time	5 (1.7)	Waste	4 (0.9)
Space	4 (1.3)	Product qual.	4 (1.4)	Soil pollut.	3 (0.6)
Noise	1 (0.3)	Trip counts	2 (0.7)	Modal split	2 (0.4)
Safety (Privacy)	1 (0.3)	Waste	2 (0.7)	Ozone pollut.	2 (0.4)

*SO2 (13), CH4 (12), HC (8), VOC (8), N2O (7), SOx (5), NO2 (4), H2O (2), NO (2), CH (1), NH3 (1), PO4 (1), THC (1)

In terms of social sustainability, travel times, traffic density and congestion, as well as customer waiting times and health issues seem to be particularly important performance metrics, while customer acceptance, private costs, space restrictions, noise implications, and privacy invasion have barely been researched as criteria for social issues. In turn, economic sustainability is often assessed by means of various cost factors (e.g., investment costs; Tan et al. 2009), asset utilization, and travel times or mileages of the operating transportation fleet, whereas current research falls short on economic performance metrics such as profits, vehicle standing times, product quality, trip counts, and waste. Finally, environmental sustainability is commonly evaluated in terms of CO_2 emissions, energy consumption, mileage, NO_x emissions or a combination of different emission factors such as SO_2, CH_4, HC, VOC, N_2O, SO_x, NO_2, or H_2O. In contrast, few simulation studies have focused on quantifying transport-related effects on noise, waste, soil pollution, modal split or ozone pollution.

Looking at Figure 1, it becomes obvious that the scholarly interest in sustainability metrics in the transportation domain has grown substantially over the recent years. While between 1996 and 2000 only one publication each assessed the social and economic impacts in the transportation sector, this number has steadily increased until 2020. Nowadays, the majority of simulation-based research even focuses on metrics related to environmental and social sustainability, indicated the increasing importance of these dimensions. Further, based on the given data, it can be predicted that the total number of publications for 2021-2025 will increase again compared to 2016-2020.

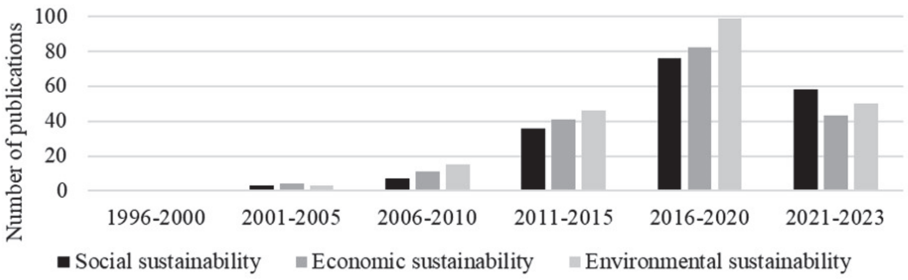

Figure 1: Simulation studies on sustainability metrics per year (339 articles total)

Referring to the specific use of individual simulation methods for the assessment of different sustainability metrics, we have conceptualized our findings based on the classifications proposed by Beese et al. (2019) and and Jahangirian et al. (2010), who distinguish the following simulation techniques: Agent-based Simulation (ABS), Analytical Simulation (AS), Artificial Neural Networks (ANN), Discrete-event Simulation (DES), Hybrid Simulation (HS), Microsimulation (i.e. traffic simulation) (MI), Monte Carlo simulation (MC), Spreadsheet Simulation (SP), and System Dynamics (SD). In this context, Table 2 provides an overview of the most common simulation methods for each of the identified sustainability metrics. Regarding social sustainability metrics, ABS appears to be a popular method for investigating customer acceptance, modal choices, service levels, space implications and utilization effects, while microsimulation is primarily used to assess noise levels, privacy concerns, traffic congestions, as well as travel and waiting times. For economic metrics, ABS is often used to evaluate costs, fleet size, market share, mileage, travel time and utilization, while AS is commonly employed for studies related to energy consumption, mileage and product quality. In turn, DES generally refers to market share, revenue, standing time, travel time or waste metrics. Yet again, MI studies frequently deal with fleet size and trip counts as major economic indicators. Ultimately, environmental metrics such as emissions (e.g., CO_2, NO_x) are commonly assessed by means of AS and MI, while mileages and waste volumes are evaluated more often via ABS. Modal choices are exclusively studied by AS, whereas more specific metrics like ozone and soil pollution are predominantly subject to studies leveraging HS, MI, or MC.

Figure 2 synopsizes the share of simulation studies that focus on urban, sub-urban, rural, or mixed transportation settings (left side), and highlights the portion of publications with different geographical scope.

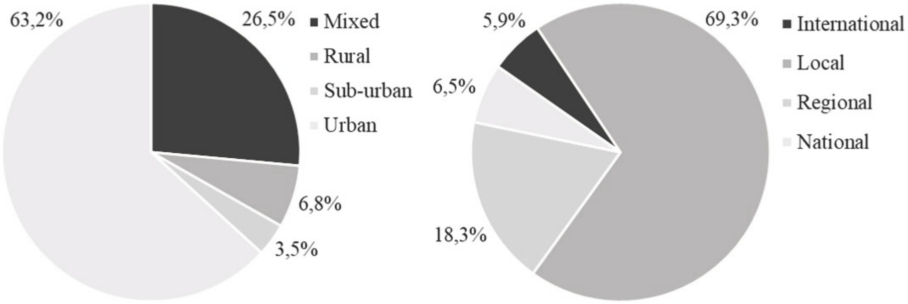

Figure 2: Setting (left) and scope (right) of transportation activities studied

Finally, Figure 3 shows the composition of transportation types (i.e., freight) across the three sustainability dimensions for different transportation modes based on their relative proportions. Here, for example, we can observe that multimodal transportation modes are investigated in terms of both, social, economic, and environmental sustainability as well as freight, people, and mixed transportation.

Table 2: Assessed sustainability metrics by simulation method

		ABS	AS	ANN	DES	HS	MI	MC	SP	SD
Social	Acceptance	60%	0%	0%	20%	0%	20%	0%	0%	0%
	Accessibility	7%	7%	7%	27%	13%	33%	7%	0%	0%
	Costs	20%	20%	0%	0%	20%	0%	0%	0%	40%
	Modal split	40%	40%	0%	0%	0%	10%	5%	0%	5%
	Noise	0%	0%	0%	0%	0%	100%	0%	0%	0%
	Safety (Health)	20%	16%	4%	4%	4%	36%	8%	0%	8%
	Safety (Privacy)	0%	0%	0%	0%	0%	100%	0%	0%	0%
	Service	35%	15%	0%	10%	5%	20%	10%	0%	5%
	Space	50%	0%	0%	0%	0%	25%	25%	0%	0%
	Traffic density	25%	16%	0%	5%	4%	38%	3%	1%	7%
	Travel time	15%	12%	0%	12%	3%	53%	4%	0%	3%
	Utilization	33%	0%	0%	33%	0%	0%	17%	0%	17%
	Waiting time	24%	9%	0%	15%	6%	33%	9%	0%	3%
Economic	Costs	21%	5%	1%	19%	4%	14%	11%	0%	4%
	Energy cons.	0%	41%	0%	5%	5%	23%	9%	0%	18%
	Fleet size	38%	15%	0%	15%	8%	0%	23%	0%	0%
	Market share	23%	15%	0%	31%	8%	0%	15%	0%	8%
	Mileage	27%	32%	0%	14%	9%	0%	18%	0%	0%
	Product quality	0%	67%	0%	0%	0%	0%	0%	33%	0%
	Profit	20%	20%	0%	20%	0%	0%	20%	0%	20%
	Revenue	18%	18%	0%	29%	0%	18%	6%	0%	12%
	Standing time	20%	0%	0%	60%	0%	20%	0%	0%	0%
	Travel time	21%	18%	0%	32%	4%	14%	7%	0%	4%
	Trip counts	0%	0%	0%	0%	0%	100%	0%	0%	0%
	Utilization	29%	12%	0%	26%	6%	6%	12%	3%	6%

	Waste	0%	0%	0%	100%	0%	0%	0%	0%	0%
Environmental	CO emiss.	10%	27%	0%	20%	0%	37%	3%	0%	3%
	CO_2 emiss.	12%	20%	0%	17%	4%	28%	6%	2%	11%
	Energy cons.	17%	28%	2%	12%	3%	27%	6%	2%	2%
	GHG emiss.	19%	23%	0%	8%	4%	23%	15%	4%	4%
	Mileage	33%	17%	2%	13%	2%	11%	13%	0%	9%
	Modal split	0%	100%	0%	0%	0%	0%	0%	0%	0%
	Noise	14%	29%	0%	0%	14%	29%	14%	0%	0%
	NO_x emiss.	9%	20%	0%	11%	0%	43%	7%	0%	9%
	Other emiss.	6%	28%	1%	22%	3%	27%	7%	0%	4%
	Ozone pollut.	0%	50%	0%	0%	50%	0%	0%	0%	0%
	PM emiss.	18%	18%	0%	11%	3%	34%	8%	0%	8%
	Soil pollut.	0%	0%	0%	0%	33%	33%	33%	0%	0%
	Waste	50%	0%	0%	0%	0%	25%	25%	0%	0%

On the contrary, electric bicycles have only been investigated in terms of economic and environmental performance metrics for mobility (i.e., transportation of people) systems, while research on electric trucks is scare concerning social performance implications and logistics (i.e., transportation of freight) systems.

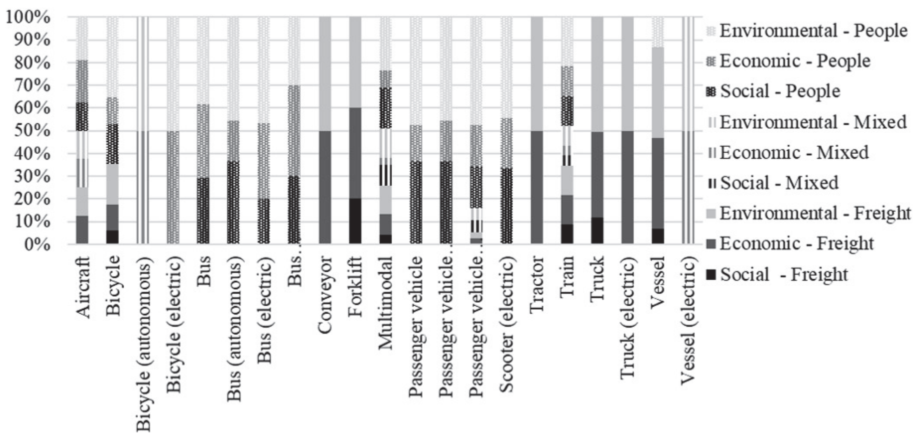

Figure 3: Type and mode of transportation by sustainability dimension

For the entire list of publications that has been reviewed for this study, please refer to the following DOI: 10.21227/q3ek-sp50

5 Conclusion

This study conducted an extensive literature review on publications that employed computer simulation to assess sustainability metrics in the transportation domain. We screened a total of 339 relevant articles and identified 39 commonly employed performance metrics across the three sustainability dimensions. Our study has shown, that sustainability metrics have become increasingly important in simulation research over the last decades, with social sustainability, comprising performance metrics such as travel times or traffic density, being the most prominent dimension within recent years. By linking simulation methods with sustainability metrics, our study provides a valuable foundation for future research when it comes to planning and conducting simulation-based research on sustainability issues. Furthermore, it identifies research trends and gaps in the transportation domain based on various side constraints such as transportation setting, transportation scope, or transportation mode and can be used to detect fruitful areas for future simulation-based sustainability research. Overall, our study contributes towards a better understanding on the use of simulation for quantifying or evaluating sustainability-related implications in the public and private transportation sector, which can support future research in developing more rigorous and efficient simulation models. Moreover, it aids decision- and policy-makers by providing guidelines and orientation regarding the choice of relevant key performance indicators for measuring sustainability of certain transport modes, which is likely to benefit the planning of more sustainable mobility and logistics concepts in the future.

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