IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received 11 March 2024, accepted 13 April 2024, date of publication 25 April 2024, date of current version 9 May 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3393470

SURVEY

A Comprehensive Survey and Future Directions on Optimising Sustainable Urban Mobility

TATIANE BORCHERS[1,2], DIRK WITTOWSKY[1], AND RICARDO AUGUSTO SOUZA FERNANDES[3], (Senior Member, IEEE)
[1]Institute of Mobility and Urban Planning, Department of Structural Engineering, University of Duisburg-Essen, 40219 Essen, Germany
[2]Graduate Program in Urban Engineering, Civil Engineering Department, Federal University of São Carlos, São Paulo, São Carlos 13565-905, Brazil
[3]Electrical Engineering Department, Federal University of São Carlos, São Paulo, São Carlos 13565-905, Brazil

Corresponding author: Tatiane Borchers (tatiane.borchers@stud.uni-due.de)

This work was supported in part by the Deutscher Akademischer Austauschdienst (DAAD) under Grant 57645446, in part by the Coordenação de Aperfeiĉoamento de Pessoal de Nível Superior (CAPES) under Grant 88887.682401/2022-00, in part by the São Paulo Research Foundation (FAPESP) under Grant 2023/00182-3, in part by the National Council for Scientific and Technological Development (CNPq) under Grant 406453/2021-7 and Grant 305215/2022-1, and in part by the Open Access Publication Fund of University of Duisburg-Essen.

ABSTRACT Climate change is currently the biggest environmental threat, being the cities responsible for a significant impact on greenhouse gas emissions. In this sense, the transport sector is among the main causes for both emissions and the depletion of non-renewable resources. Considering this scenario, there is an appeal to build more accessible, smart, sustainable and energy-efficient cities, promoting energy transition in urban systems and increasing the quality of urban life. This review aims to analyse transport and urban mobility studies that employ optimisation techniques to achieve environmental-related, sustainability, energy transition or climate change mitigation goals. After an overview regarding modelling aspects of how such goals were addressed, the nature of the objective functions, the perspectives considered, and the network application, such studies were classified into five areas and further detailed. The areas comprise: (i) planning and policy-making; (ii) environmental variables; (iii) demand and traffic management; (iv) technology and energy; and (v) non-spatial measures. In this sense, future research directions should include optimisation models that consider the social aspects of transport and the interests of passengers, operators, and the community simultaneously, improve the modelling of environmental impacts to increase its robustness, and deal with large network problems.

INDEX TERMS Climate change, greenhouse gas (GHG) emissions, optimising, passenger urban transport, sustainable mobility.

I. INTRODUCTION

Cities have a significant impact from the point of view of greenhouse gas (GHG) emissions, as most traffic, industry, commerce, and over 50% of the world's population is located in urban areas. This number is expected to be around 68% by 2050 [1]. The rapid growth of the urban population and the consequent increase in demand for travel have also raised awareness of the transport sector's contribution to GHG emissions and the urban effects of climate change [2].

In order to mitigate the effects of climate change, low-carbon transport plans are needed, including a set of policies and strategies to avoid and reduce unnecessary motorised travels, shift existing travels to more efficient and low-carbon modes by encouraging the use of public transport and non-motorised modes, and improve transport technologies to reduce GHG emissions by promoting fuel economy, electric mobility and the use of sustainable energy sources. A range of actions can be taken to change people's mobility behaviour and create a culture of sustainable mobility. These include redistributing the road space giving priority to public transport, cycle networks, and sidewalks, restricting parking spaces, reducing road speeds, creating road price schemes, enhancing multimodality experience for door-to-door travels, raising the public awareness of the impacts of transportation on the climate crisis, and also including

The associate editor coordinating the review of this manuscript and approving it for publication was Huaqing Li.

public participation into transport and urban planning [3], [4], [5], [6]. As for guidelines, the European Union strongly recommends that European cities embrace the concept of Sustainable Urban Mobility Plans (SUMPs). Around the world, many cities have transport planning frameworks that, if not officially denominated as SUMPs, closely resemble them, embodying a comprehensive approach to fostering sustainable transportation strategies [5].

Among transport techniques and technologies, optimisation processes can be considered prominent for building smarter and more sustainable cities, as they may contribute to generate city structures and forms that improve efficiency, equity, and quality of life. Operations research, the field where optimisation techniques are inserted, took great advantage of technological advancements. Over the last decades, enhancements in both methods and algorithms allowed to tackle larger problems. In general, transportation optimisation supports the decision-making process by applying advanced analytical methods, and can be applied into the above-mentioned range of actions towards sustainable mobility. Thus, optimisation techniques can contribute to create sustainable mobility plans and to address the big global challenges as climate change. However, global challenges are highly complex and must be addressed interdisciplinary, otherwise a field or area of research might become insular [2], [7].

Optimisation techniques have been applied in transport studies for a variety of reasons, but mainly for the design and operation of networks. Previous reviews have analysed mathematical modelling and optimisation techniques in studies involving network design (both of public transport and urban transport networks) [8], [9] and route design [10]. However, these reviews mainly focus on defining and classifying the problems, and describing objective functions, constraints and solution methods, sticking to an operational approach of the transport problems. Guihaire and Hao [8] present a review of optimisation formulations for the transit network design, frequencies setting, and timetabling problems. In the review of Guihaire and Hao Kepaptsoglou and Karlaftis [10], the authors specifically focus on the routing problem, while Farahani et al. [9] have extrapolated the analysis to the urban network.

On the other hand, there are reviews that analyse environmental and sustainable aspects in the transport sector, but these are either comprehensive — as Sdoukopoulos et al. [11] and Kraus and Proff [12], that had a similar work on analysing and summarising sustainable transport criteria and indicators or as is the case of Aminzadegan et al. [6] covering all modes of transport including shipping and air and scales from urban to international trips — or when the scale was restricted to urban, the focus of analysis was usually a single mode of transport as in [4], [13], [14], [15], and [16]. Miller et al. [4] summarised strategies and instruments for low-carbon urban transport, focusing on the avoid-shift-improve measures. Kwan and Hashim [13] conducted a critical review to present the relationship between public transport and sustainability, offering an overview of key concepts and how public transport contributes to sustainability goals and recommendations for planning, engineering, and researching sustainable public transport. Kwan and Hashim [14] conducted a review on co-benefits of mass public transport in climate change mitigation. Reddy and Narayana [15] presented a review on electric vehicles (EVs), where they determined five major areas of optimisation (design, energy management, optimal control, charging/discharging and routing). In terms of shared bicycles, Si et al. [16] pointed that the main topics regarding systems' optimisation include design of the network (stations and capacity), integration with public transport, and operational aspects (such as the imbalance between bicycle demand and station inventory).

Moreover, when presenting research gaps, Farahani et al. [9] highlighted the need to include objective functions and constraints that address environmental factors. Also, Agatz et al. [2] advocate transportation optimisation must support decision-making process regarding the United Nations' sustainable development goals (SDGs) [17]. In this sense, the present study proposes to fill the gap of analysing the literature in terms of how optimisation models considered sustainability aspects in urban passenger transportation. In this way, the aim of the article is to conduct a review of transport and urban mobility studies that employ optimisation techniques to achieve environmental-related, sustainability, energy transition or climate change mitigation goals. The survey seeks to present a more holistic approach to urban mobility, rather than just focusing on operational aspects, as presented in [4] and [13]. The main contribution of this review, besides updating the previous ones, was to synthesise information on how optimisation techniques can be used to mitigate climate change through energy transition and urban and transport planning.

The remainder of this article is as follows. Section II comprises the authors' understanding of promoting sustainability and sustainable urban mobility, and the benefits of sustainable transport in the context of climate emergency. In Section III the method used in this review is described. Section IV presents a general overview of the studies analysed, followed by a discussion of decision variables and objective functions, while the solution methods are shown in Section V. The research gaps and future directions are drawn in Section VI. Finally, the conclusions are brought in Section VII.

II. SUSTAINABILITY AND URBAN MOBILITY

Despite the ongoing global push towards sustainability, current urban development trends and patterns are still far from this goal, thus, the challenging process of building more ecologically conscious cities is a necessary undertake, because the quality of life of present and future generations depend on the promotion of an ecologically balanced, socially just, and economically viable environment [18], [19], [20].

Sustainability has been brought into light in the last few decades and although its concept is not definitive, it is usually considered a paradigm of social thinking proposed to guide and shape the development of society in its prominent spheres, including science and innovation, technology, economics, urban planning, policy, and institutionalisation [18]. The Brundtland Commission Report provides a generic definition of sustainable development: ''development that meets the needs of the present without compromising the ability of future generations to meet their own needs'' [21]. Sustainability constitutes a state in which society does not harm natural and social systems for present and future generations, and economic, environmental, and social values and goals are balanced, i.e. economic development is balanced with environmental protection and social equity and justice [18]. So, usually the concept of sustainability is subdivided into three dimensions: economic, environmental, and social [11], [12], [13], [21].

Mobility plays an important role in sustainable development because of the pressure it exerts on the environment, besides its economic and social impacts. The rise of the term ''sustainable mobility'' changed the traditional approach of transport planning, which conceptualised transport as a derived demand and as infrastructure to support economic growth, to an approach that recognises the pitfalls of unrestricted economic growth, incorporating social and environmental objectives such as environmental protection and democratic participation [22]. In previous decades, transport planning sought to maximise network capacity, traffic volumes, and operating speeds, whereas the proposed sustainable mobility model focuses on people, relating to concepts such as accessibility and increasing quality of life through the regeneration of urban spaces. Sustainable mobility still involves system (infrastructure and capacity) planning, but now social aspects as mobility justice, participation, transport demand management and changing travellers' behaviour come into light [3], [5], [11], [23].

Given the Avoid-Shift-Improve framework, sustainable mobility stands for reducing the need to travel, reducing distances through land-use related policies, implementing policies for modal shift (from cars and motorbikes to active and public transport modes), and improving technology for reducing the impact of transportation in the environment [3], [4], [5], [11], [12], [20]. Not exhaustively, criteria and indicators regarding sustainable mobility (in economic, environmental, and social dimensions) include contributions to the economy and development, costs of the transport system (including costs of externalities), efficiency and reliability of the transport system, energy efficiency, social insertion of sustainable and smart technologies, consumption of fossil fuels, percentage of renewable and alternative energies in relation to total consumption in the sector, pollutant and GHG emissions, air quality, rates of respiratory diseases caused by air pollution, accident rates, congestion rates, noise pollution, fragmentation of urban space, access to public green and leisure spaces, urban accessibility, affordability, social equity, level of integration with urban planning, modal split, capacity to shift demand from individual to public and active modes and multimodality [11], [12], [13].

Urban planning and the transport sector intersections have been investigated in terms of indirect public health benefits, which were associated with measures to reduce GHG emissions, in this case considering the environmental and social dimensions of sustainability [2], [24]. Reducing or eliminating GHG emissions in the transport sector will require a broad implementation of sustainable mobility policies, which should start from the premise of integrating different objectives (economic, health and environmental), while considering the needs of different social groups. Furthermore, it also requires integration with land use policies, which can guide urban development in a way that allows public transport and active modes to be the focus of urban mobility [25], [26].

The transport sector is among the main contributors to global warming and the depletion of non-renewable resources. The sector is responsible for 14% of total GHG emissions and 23% of CO_2 emissions. Passenger cars, two- and three-wheelers and minibuses contribute about 75% of CO_2 emissions from passenger transport, while public transport (including buses and rail systems) generates about 7% of emissions, despite covering one fifth of passenger transport globally [5]. Regarding particulate matter, the road transport sector accounts for about 30% of global urban emissions [7].

In this context, there is an urgent need to determine more efficient ways of promoting sustainable and low-carbon mobility strategies. In the literature, measures to achieve this are categorised as structural / hard and as psychological / soft. Structural measures are related to planning and management (land use, transport networks, traffic, etc.), technology, economy, or policy / regulation [4], [6]. The psychological ones, on the other hand, consist of information and communication measures, and are focused on managing the car use demand by changing travellers' attitudes and behaviour. These measures may include, for example, educational and awareness campaigns, organising services, coordinating activities of different stakeholders, and personalising routes, facilitating the use of sustainable modes [27].

Aminzadegan et al. [6] conducted a review to investigate the variables affecting GHG emissions in different transport modes and divided these variables — and their respective reduction strategies — into four groups of hard measures (planning and policy-making, technology, economy, and demand). For road transport, the main solutions found for the different groups were: (1) planning and policy-making – urban planning with improved public transport and encouraging the use of public and active transport instead of private vehicles; (2) technology – adoption of alternative fuel sources with lower carbon content, zero-emission vehicles, fleet renewal and use of smart systems for route improvement; (3) economic factors – imposing fuel taxes or eliminating fuel subsidies, and converting external costs into internal costs, so that accidents, pollutants, and noise come to be considered as system costs and, in this way, the investments in transport networks for individual vehicles would be perceived as costlier; and (4) demand – managing choice of sustainable transport modes, residential densities and employment, which potential effects include reducing travel demand and dependence on motorised vehicles. On the other hand, soft measures as travel behaviour changing approaches can enhance the effectiveness of hard measures and strengthen sustainable urban mobility systems, being, therefore, an essential element of climate action [7], [27].

An effective reduction in GHG and urban pollutant emissions requires a reduction in the need of travelling and changing modes of travel, i.e. besides changing urban forms into less car dependent ones, it is also necessary a decrease in the use of individual motorised vehicles and an increase in the use of public transport and active modes, such as cycling and walking [6], [25], [26], [28], [29]. This way, policies — with significant investment — are required to make sustainable modes attractive and viable [28]. It is important to highlight that isolated measures or strategies have smaller potential effects than measures applied jointly. Furthermore, policies involving technology application, such as the electrification of bus fleets, can reduce emissions, but have smaller positive effects on human health than policies promoting active transport [29]. Thus, the combination of measures of different natures presents itself as the best alternative to amplify the environmental, economic, and social benefits that can be extracted from sustainable transport systems [6], [28], [29].

In public transport, fleet electrification combined with other mode-enhancing strategies, can be an attractant for mode shift, not only for its technological nature but also for the operational improvement of the public transport system [6], [24], [25], [26]. Route improvements and fare incentives can also be used as mode-shifting promoting strategies [6]. In addition, the benefits of any public transport system go beyond productivity itself (such as improved service regularity) and include other aspects that can impact on health, accident reduction, mobility, income and household budgets [30]. In active transport, the additional impacts involve direct health benefits, with a decrease in the prevalence of physical inactivity and various diseases. Although the increase in pedestrians and cyclists also increases their exposures to air pollution and accidents, except in extreme polluted environments, the positive effects of physical activity strongly outweighed the negative effects of traffic-induced injuries and exposure to air pollution [29], [31]. Therefore, active and public transport modes play a central role in building a smart mobility model that is environmental, economical, and socially sustainable. New forms of mobility like Mobility as a Service (MaaS), including, for example, bike-sharing systems, may also make private cars less attractive than public, shared or active transport modes; integration of different fares, payment systems, and modes may also improve the user experience with sustainable modes [7], [32]. However, some MaaS solutions also raise concerns. While private vehicle ownership can indeed be replaced by shared vehicles or shared journeys, this may not necessarily mean fewer kilometres travelled by car, and consequently, emissions reduction. Another point of concern is that some MaaS services, such as ride-sourcing, can replace journeys by public transport, since they offer greater convenience for door-to-door journeys [33].

Once a decrease in using individual motorised vehicles is achieved, the further step should be to reduce the emissions of the remaining car fleet. In this sense, EVs can diminish oil and natural gas resources consumption once they are powered by renewable energy sources. Caution is needed, however, as an increase in the use of EVs without a mode shift or without a transition of energy production to renewable sources may imply a reverse effect, increasing fossil energy and non-renewable resources consumption [15], [34].

III. METHOD

The methodology of this study comprises a systematic review of the literature on transport and/or urban passenger mobility studies that use optimisation techniques to achieve environmental-related, sustainability, energy transition or climate change mitigation goals.

Following the method proposed by Tranfield et al. [35], the execution of this review has three main stages: i) planning the review; ii) conducting the review; and iii) reporting and disseminating the results. During the planning phase, the need for a research review was identified, then a proposal for it was prepared, as well as the protocol for conducting the review. In the conducting stage, searches were carried out in databases of scientific articles, followed by the application of inclusion and exclusion criteria, and data extraction and synthesis. Last, the dissemination of results includes the writing of this survey, containing the recommendations for furthering the research in the area.

In the planning stage of the review, an initial search was conducted using the terms:

> ((“sustainab*” OR “climate chang*”) AND (“urban mobility” OR “urban transport*”) AND (“optimisation” OR “optimization”) AND (“review” OR “bibliometri*” OR “state-of-the-art”))

to check if any similar reviews already existed in the literature. No papers similar to the one proposed in this study were located, which encouraged the authors to proceed with the initial proposal.

Once the alternatives for promoting sustainability in urban mobility had been established, as presented in Section II, the following inclusion and exclusion criteria were defined:

Inclusion:

- Transport and/or urban passenger mobility studies that employ optimisation techniques to achieve environmental-related, sustainability, energy transition or climate change mitigation goals.

Exclusion:

- The study is not related to the area / scope proposed in this review;
- The study does not promote policies related to active modes and public transport;

- The study does not concretely include aspects of sustainability and/or climate change, i.e. the terms are only mentioned superficially and are not a focus of the study;
- The scale of the study is not urban (or metropolitan), i.e. it does not work with urban transport or urban mobility;
- The study is not about urban passenger transport / mobility;
- The study does not apply optimisation techniques;
- The study has methodological issues and was excluded because of quality standards;
- It is not possible to extract the questions from the established protocol.

The review protocol also included the following extraction questions:

Q1: Which modes of transport are considered in the study?

Q2: What does the study analyse in relation to transport? Categorisation into network infrastructure (roads or stations), energy infrastructure (energy stations/vehicle charging or distribution network), transport system operation (which stage of system operation?), energy operation, modal integration (which modes?), demand management (how?).

Q3: What sustainability or climate change mitigation strategies (e.g. emissions reduction) are used in the study? Categorisation into policy, economic, technological and demand management strategies.

Q4: What aspects of sustainability were considered?

Q5: Which perspectives are considered in the optimisation model? Categorisation into passengers or users of the transport system, operators, citizens / government / community.

Q6: What are the model's decision variables?

Q7: What are the model's objective functions?

Q8: What are the model's solution methods?

Q9: What type of network is the optimisation model applied to?

Q10: Is there a performance analysis of the solution algorithm or the mathematical model?

Once the review protocol had been defined, the following search term was established:

TITLE-ABS-KEY ((''sustainab*'' OR ''climate chang*'' OR ''environmental impact'' OR ''transport* emissions'') AND (''public transport*'' OR ''transit'' OR ''active transport*'' OR ''bicycle*'' OR ''bike*'' OR ''cyclist'' OR ''walk*'' OR ''pedestrian*'' OR ''modal split'' OR ''modal share'' OR ''urban mobility'' OR ''urban transport*'' OR ''city mobility'' OR ''city transport'' OR ''smart mobility'' OR ''e-mobility'' OR ''green transport'' OR ''green mobility'' OR ((''city'' OR ''urban'') AND (''road network'' OR ''transport infrastructure'' OR ''transport network''))) AND (''optimisation'' OR ''optimization''))

The searches were conducted on the SCOPUS platform and updated until January 2023 to include all studies published until 2022. Filters were applied to the database to keep only articles and reviews published in journals. As a result, the initial search contained 659 articles, which titles were analysed, and, subsequently, 348 had their abstracts screened.

Alongside the reviewing process, studies not related to the mobility/transport area were eliminated (n = 221), and also those that mentioned sustainability or related terms in the abstract, but whose content aimed to promote mobility by private vehicles, with no technology or similar component to limit emissions or reduce the impacts of the mode (n = 22). Studies covering regional transport or even national transport infrastructure were also excluded (n = 16), as well as studies related to logistics and freight transportation (n = 101), as they do not fall within this review scope. Finally, articles initially returned with terms related to ''optimisation'' or ''optimal'' but which did not apply optimisation techniques as a methodological proposal were excluded (n = 93). In the final analysis, 166 articles were included in this review; at the final stage, articles that did not meet the minimum quality criteria (e.g. confusing modelling) (n = 11) or articles from which the protocol questions could not be extracted (n = 29) were also eliminated. Figure 1 shows the process of excluding articles and the delimitation of the articles considered in the final analysis.

For the results' dissemination stage, the articles were divided according to the following criteria: (i) planning and policy-making – studies that focused on promoting or improving sustainable transport modes, involving mainly infrastructure and operation aspects (60 articles); (ii) environmental variables – studies that explicitly include environmental variables or transport emissions in their optimisation models (38 articles); (iii) demand and traffic management – studies integrating transport and land use planning and those that aimed to improve congested networks (23 articles); (iv) technology and energy – studies that analyse technological enhancements and energy systems, such as EVs and alternative fuel sources with lower carbon content (40 articles); and (v) non-spatial measures – studies that include economic and other non-spatial factors (five articles). This structure was based on areas for controlling GHG emissions in transportation (planning and policy-making, demand, technology, and economics) presented by Aminzadegan et al. [6], while the studies working explicitly on environmental variables were accommodated in an exclusive subsection.

It is worth mentioning that, as the studies in this research deal with sustainable mobility and transportation, they are aligned with the Avoid-Shift-Improve framework [3], [4], [5], [11], [12], [20]. In this sense, the avoid strategy comprises the demand management studies, where land use and transport planning are analysed together; the shift approaches are based on planning and policy-making, environmental, traffic management, and non-spatial measures, seeking for improvements on the active modes and public transport; and the improve ones comprise studies focused on

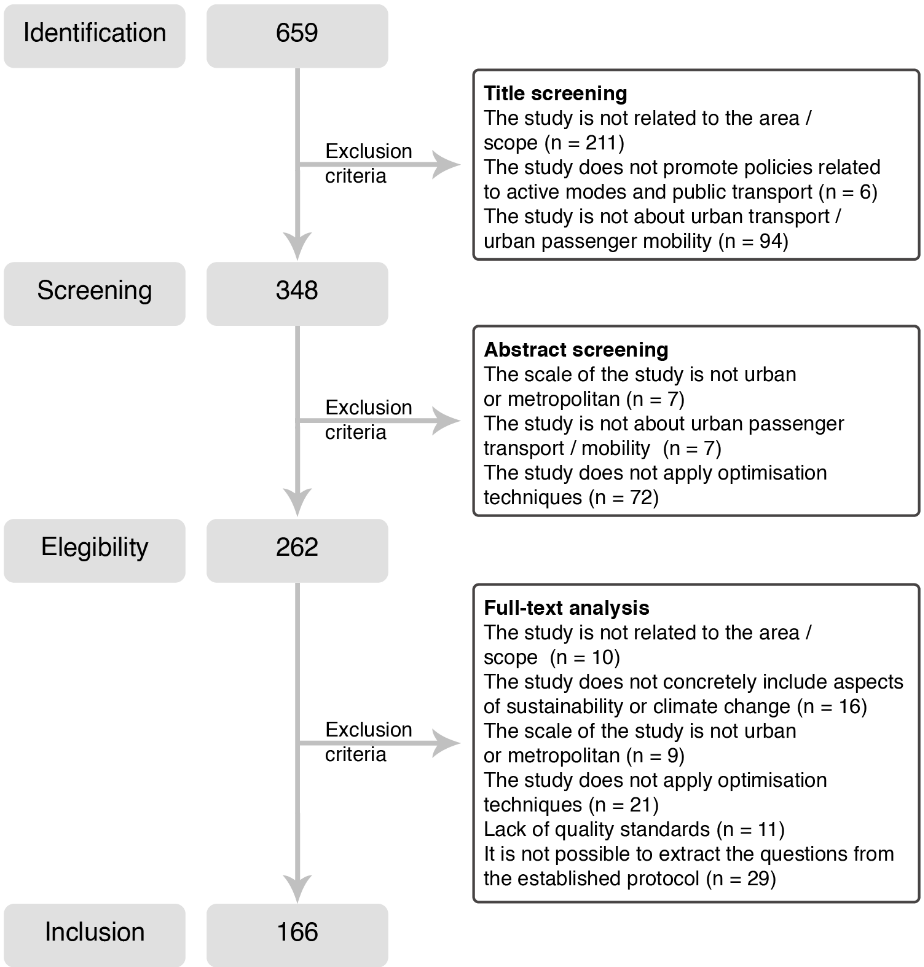

FIGURE 1. **Studies' selection flow diagram.**

technology and energy, environmental, and traffic management. As the Avoid-Shift-Improve-based approaches are more intertwined, it is difficult to classify the optimisation articles into a single category. In this way, the structure proposed by Aminzadegan et al. [6] was considered to better systematise the organisation of optimisation studies.

As most studies considered in this survey focused on more than one of the above-mentioned aspects, they were classified according to their main purposes, allowing to obtain a broad oversight of the field, as presented in the next section.

IV. PROMOTING SUSTAINABLE MOBILITY THROUGH OPTIMISING

A general analysis of the literature includes the aspects considered in modelling optimisation problems, as presented in Table 1. From the total number of articles included in this review (166), 62 considered the environmental dimension of sustainability, mostly related to reducing emissions and energy consumption; these environmental variables will be further explored in Subsection IV-B. However, only 10 and 11 of them also considered economical and social aspects, respectively. One may argue that optimising costs may indicate economic sustainability, and indeed this is the main approach to address this dimension, but only studies that explicitly state they are looking at this aspect have been included in this general analysis. Regarding the social dimension, problems addressed noise pollution, accessibility, social equity, network fairness, travel times, and the Gini coefficient. Only four articles considered the three dimensions all together [36], [37], [38], [39].

Regarding how the problem was modelled, there were single and multi-objective functions, besides problems formulated at multiple levels. In terms of multiple levels, frequently the lower level relates to trip distribution, modal split and/or traffic assignment models [37], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50], [51], [52], [53]. Moreover, the perspectives were considered related to: (i) passengers – considering their behaviour or interests (e.g., number of transfers, travel distance and time, and comfort); (ii) operators – minimising costs or investments and maximising profit; and (iii) community – environmental and external costs and integrating urban and transport planning. Most of the articles focused on the operators' perspective (59 of 166), but some studies already analyse more than one perspective.

It is worth mentioning that objective functions may not necessarily be related to the transport mode or the application of the model, as they may represent goals which can be extrapolated to different modes and applications, such as reduction of travel times or costs. Another remark is that the same function can represent different perspectives. In order to solve the optimisation models, the studies used both mathematical programming-based commercial solvers and heuristics/metaheuristics.

Network application regards where the model was tested. Some authors applied their models to theoretical networks or presented numerical examples, while others tested in benchmark networks as Sioux Falls [44], [49], [52], [53], [54], [55], Mandl [56], [57] and Nguyen–Dupuis [50], [58]. Nevertheless, in the vast majority of studies, the model was tested on real networks or real case studies. Approximately 55% of the studies investigated cities in Asia, 20% in North America (USA and Canada), 18.5% in Europe, only four per cent in Latin America and two per cent in Oceania; no case studies were found in African cities. From the Asian applications, China was the country with more studies (comprising 48 articles [38], [40], [41], [46], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102]), from which Beijing stands out with 17 studies [62], [63], [65], [74], [80], [81], [83], [84], [85], [87], [88], [92], [93], [94], [96], [98], [102]. Real networks or case study applications may include universities' campi [36], [103], [104], [105], [106], [107], [108], neighbourhoods and districts [46], [80], [95], [98], [102], [109], or studies that only consider some transport lines/stations within a city or transport network [71], [81], [86], [93], [96], [110], [111], [112].

A. PLANNING AND POLICY-MAKING

For planning and policy-making studies, optimisation techniques were applied mainly for infrastructure and operation planning, but some authors also considered other purposes as integration with land use planning, traffic management, and modal integration.

In terms of infrastructure planning, Murray and Feng [109] was the only study that considered the mode of transport of walking and the authors were looking to determine an optimal street lighting scheme. For bike-sharing systems, problems related to infrastructure considered the location of stations [78], [148], [156], [174]. Focusing on specific aspects of the studies, Hu et al. [174] defined as decision variables the location of new stations, the removal of old ones without affecting the performance of the system, and the reallocation of docks between stations; Yang et al. [78] considered dynamic demand in their problem; Askarzadeh and Bridgelall [156] considered covered activity points, such as the presence of transit stops, parks, restaurants, commercial areas, industrial centres, and universities in areas of high population density to determine the station areas; and Qian et al. [148] included disadvantaged communities and park areas in their formulation. Related to rail systems, Kang et al. [152] aimed at selecting the points of intersections of the new railway alignment, while Chen et al. [154] sought to determine the locations and capacity of rail-based park-and-ride sites.

For multimodal networks, studies aimed to determine the location and capacity of the transfer infrastructure to be built [52], a set of alignments covering as much of the travel demand as possible [176], and to design a multimodal public transport system with taxi-sharing and subways, providing door-to-door service [92]. Besides that, considering the occurrence of natural disasters, Mera and Balijepalli [51] proposed a model for road maintenance to improve the resilience of the network.

For optimising operation strategies, the fleet management was the main approach of bike-sharing systems, focusing on distributing and repositioning bikes between stations, i.e. rebalancing the fleet within the system [72], [82], [101], [150], [175], [179], [182], [191], [192]. Wu et al. [179] sought to elaborate an incentive plan for users to perform the repositioning activities, Fan et al. [182] sought to determine the fleet size, while Zhang et al. [82], Cao and Xu [192] and Zhou et al. [101] elaborated repositioning plans, including routes, scheduling of the operation [82] and number of bicycles [192]. The study of Chang et al. [84] distinguishes itself by incorporating damaged bicycles into the model.

Regarding bus systems, the modelling involved network design (station location and routes), frequencies setting, bus scheduling and fleet sizing. For the network design, studies sought to determine public transport service area [147], bus routes [76], [90], [195], route length [68], [74], number of lines [74], and stop/station location [74], [76], [199]. For time and vehicle related modelling, studies focused on frequencies setting problems [53], vehicle scheduling [62], [67], [110], [185], and timetabling strategies [79], [169]. Some authors modelled more than one aspect, for example routes and frequencies setting [194], routes and vehicle scheduling of a customised bus service [89], routes and timetabling [187], frequencies setting and timetable development [193], and service area, frequencies, and vehicle scheduling [164]; Nesheli et al. [127] focused on real-time operation aspects of bus systems, as vehicle holding time and boarding limit at stops, and also deciding if the vehicle could skip certain stops. Finally, for rail systems, studies focused on determining train timetables and rolling stock schedule [63], a conflict-free timetable for all trains running on a railway, considering multiplatform stations [172], frequencies setting and operational aspects (stop scheme and operation time) [93], rail scheduling and fleet management [100], and a transit-based evacuation plan for rail transit line emergencies [71].

Infrastructure and operation planning, integration with land use, traffic management, energy and modal integration in the optimisation model were also combined in some articles. For bike-sharing systems, studies integrated network design (station location and/or capacity) and fleet sizing

TABLE 1. Taxonomy of studies in terms of modelling aspects.

Modelling aspects	Specification	Articles	References
Sustainability	Economical	10	[36–39, 107, 113–117]
	Environmental	62	[36–38, 40–44, 46, 48, 49, 55–61, 65, 66, 72] [81, 85, 87, 88, 97, 102, 104, 113–116, 118–146]
	Social	11	[36–39, 49, 53, 59, 65, 135, 135, 147, 148]
Objective functions	Single objective	104	[39, 55, 57, 60, 62, 64, 66–72, 74–78, 80, 82–84] [86, 89, 90, 92–94, 96, 99–103, 105–109] [111, 113, 114, 116–119, 122–128, 130, 132–135] [137–139, 142, 143, 145–147, 149–186]
	Multiple levels	25	[37, 40–47, 49–54, 58, 61, 63, 73, 95, 98, 112, 187–189]
	Multi-objective	37	[36, 38, 48, 56, 59, 65, 79, 81, 85, 87, 88, 91, 97, 104, 110] [115, 120, 121, 129, 131, 136, 140, 141, 144, 148, 190–201]
Perspectives	Passengers	9	[68, 93, 99, 127, 147, 151, 156, 174, 190]
	Operators	59	[45, 47, 50, 54, 64, 69, 72–75, 77, 80, 84, 86, 92] [96, 98, 100, 101, 103, 105–108, 111–113, 116, 117, 126] [152, 154, 155, 159, 160, 163, 165–168, 170, 171, 173] [175–178, 180–185, 187, 189, 191, 192, 198, 201]
	Passengers and operators	39	[51–53, 62, 63, 67, 70, 71, 76, 78, 79, 82, 83, 89, 90, 94, 95] [109, 110, 138, 150, 153, 157, 164, 172, 179, 186] [148, 158, 162, 169, 188, 193–197, 199, 200]
	Passengers and community	4	[56, 135, 137, 161]
	Operators and community	21	[36, 40, 46, 61, 66, 102, 114, 115] [119–123, 128–131, 133, 136, 142, 146]
	Passengers, operators, and community	34	[37–39, 41–44, 48, 49, 55, 57–60, 65, 81, 85, 87, 88, 91, 97] [104, 118, 124, 125, 132, 134, 139–141, 143–145, 149]
Network application	Theoretical networks or numerical examples	27	[37, 42, 43, 45, 47, 48, 55, 113, 121, 122, 124, 125, 135] [143, 145, 147, 150, 164, 167, 169, 172, 178, 179, 182] [187, 189, 191]
	Benchmark networks	12	[44, 49, 50, 52–58, 200, 201]
	Real networks	124	[36, 38–41, 46, 51, 59–103, 105–112, 114–119, 126–128] [130–134, 136–142, 144, 146, 148, 149, 151–163, 165, 166] [168, 170, 171, 173–177, 180, 181, 183–186, 188, 190, 192–199]

and management [73], [98], [134], [153], [186]. For buses, Wu et al. [124] sought to determine optimal travel speed and waiting time at bus stops to avoid waiting time at signalised intersections, considering operation and traffic management. For studies involving cars, the main topics were related to road and traffic management. Luo and Yang [160] selected roads for restoration to provide quick disaster response, Bi et al. [83] developed reward mechanisms to improve travel and energy efficiency of a road transportation network by establishing a task recommendation system, and to prepare urban transport systems for long-term disasters [94]. For multimodal networks considering both bus and car traffic, Khoo et al. [190] studied the implementation of exclusive bus lanes and its period of operation, Li et al. [47] focused on bus scheduling and fuel surcharges, Haitao et al. [173] proposed a strategy to provide public transport priority in the perimeter of urban networks, and Gao et al. [70] focused on traffic lights operation, aiming at providing bus priority on arterial roads. At last, for a multimodal network to integrate buses to the rail system, Almasi et al. [196] focused on network design (routes), frequencies setting, and operational aspects (dwell time).

Considering the perspective of passengers alone, studies sought to minimise uncovered demand [174], distances in the network [156], and passengers' travel time [68], [93], [127], [190], and maximise accessibility [147] and direct transfers without waiting [127]. For the operators' perspective alone, studies aimed at minimising costs or maximising revenue [84], [98], [100], [101], [152], [154], [160], [182], [185], [192], minimising travelled distance or vehicle mileage [72], [73], [74], [92], [175], [187], [191], minimising workload [73] and rebalancing amount [192], maximising covered demand [73], [176], rebalancing utility [191], the total social net benefit [47], and the average passenger flow [173].

Studies that combine passengers' and operators' interests usually combined functions of both perspectives. As some problems are single objective, considering both perspectives normally is done by including penalties or constraints for unsatisfied demand [150], [186], travel times [164] or service level [179] in a problem focused on the operators' perspective; in the case of Hou et al. [71], contrary to the main approach above-mentioned, the objective function aimed at maximising the total number of stranded passengers transferred due to rail emergencies, with constraints related to the operators' perspective, such as vehicle fleet, headway and time constraints. For multi-objective or multi level problems, the most frequent combination of functions was minimising passenger's travel time and operators' costs. Nevertheless, the whole range of functions aimed at: minimising costs or maximising revenue [53], [63], [67], [83], [89], [94], [110], [148], [150], [164], [179], [186], [194], [195], [196], [199], minimising unsatisfied demand costs [110], [196] and user costs to access the service [199], maximising covered demand or ridership [52], [62], [76], [78], [153], maximising accessibility [148] and network fairness [53], and minimising distances [78], fleet size [169], vehicle's transportation time [82], passengers' waiting time [63], [79], [82], [169], passengers' travel time [51], [90], [169], [193], [194], vehicle mileage [193], energy consumption [79], vulnerability [51], intersection delay [70], train infeasibility [63] and train delay [172]. Lastly, only two studies considered all the three perspectives (passengers, operators, community) simultaneously, and they sought to minimise design and operation costs [134] and bus operational costs (delay, stops, acceleration) [124].

It is worth mentioning that functions with costs may represent rebalancing (in bike-sharing systems) [182], operation [53], [67], [100], [110], [164], [185], [194], [199], transportation/travel [67], [101], [154], [194], [199], time [160] or generalised [84], [152] costs. Also, revenue is used as an umbrella term and may include other similar terms, such as profit and benefit. This consideration was made in order to improve the readability and clarity of this review article. As final remarks, it is interesting to point out that Luo et al. [72], Wu et al. [124], Nesheli et al. [127], and Zhang et al. [134] analysed GHG emissions in their studies, but the estimates were not included in the optimisation model. More details of the studies presented in this subsection can be found in the Appendix.

B. ENVIRONMENTAL VARIABLES

This subsection comprises studies that explicitly included environmental variables or transport emissions in the optimisation models. As most of these studies focused on reducing emissions, optimisation has been applied to infrastructure, energy, and operation planning, traffic management, modal integration, and new mobility forms.

Although systems related to cycling are currently the focus of several researches in urban mobility, the inclusion of sustainability or environmental aspects in optimisation problems formulated for such systems is still scarce. In this sense, only three studies could be considered within this subsection. Doorley et al. [135], considering a network of cars and bicycles, sought to design cycling networks. For bike-sharing systems, Gámez-Pérez et al. [131], in a network design problem, aimed at determining the number and location of stations, and Wu et al. [102] focused on creating a bike rebalancing scheduling plan using EVs. For buses, studies applied optimisation to design the main powertrain components of electric buses (fuel cell, electric motor, and battery) [120], [129], for locating charging facilities [36], [39], [133], for network design (routes) and frequencies setting [56], [57], [81], [118], fleet composition [81], [122], and vehicle scheduling [81], [119], [123], [132]. In rail systems, studies sought to determine station location [144] and to elaborate a dynamic operation plan for a ventilation control system in metro stations [138]. There were two studies that focused on shared mobility, aiming at determining station location [141], routes, scheduling, and fleet sizing of shared systems in suburban contexts [142]. Studies that considered only cars as mode of transport focused on road segment deployment [114], traffic routing/management [44], [49], [139], traffic signal plans [137], and on the deployment of cordon-based pricing tolls [48].

Multimodal studies included a variety of mode combinations and decision variables. Si et al. [43] analysed policy measures as congestion tolls and transit fares considering bicycles, buses, and cars. Li and Lu [87] aimed at determining an optimal urban passenger transportation structure, considering bicycles, buses, rail systems, and cars. Meng et al. [55] proposed a model for multimodal traffic assignment in a network with buses, electrical bicycles, and cars. For networks considering buses and cars, Sharma and Mathew [42] analysed the expansion of road network capacity and Ye et al. [146] sought to determine the deployment and operation of recharging facilities for buses and private EVs. Asghari et al. [140] aimed at designing a sustainable and efficient ride-sharing service (employee transportation service), considering as alternative options the private cars and the public transport by bus. Authors investigated public transport (buses and rail systems) through network design (station location and routes) and frequencies setting [143], [145] and through an analysis for establishing an effective subsidy scheme to reduce GHG emissions [61]. Feng et al. [40] investigated car ownership and number of trips in a network considering cars and other modes; Yang et al. [41] had a similar approach considering buses and cars, focusing on estimating the maximum car ownership per zone and subsequent network flow. Finally, Qiang et al. [66] had a similar purpose of Li and Lu [87], but additionally considering walking as a transport mode.

Regarding the objective functions, all the studies considered more than one perspective. Loy-Benitez et al. [138] considered the passengers' and operators' perspectives by minimising indoor PM_{10} concentration and ventilation energy consumption of metro stations. Regarding passengers' and community's interests, Duran et al. [56] and Abudayyeh et al. [137] aimed at minimising total travel time and CO_2 emissions, while Doorley et al. [135] sought to maximise societal benefit through a function of travel and infrastructure costs, health impacts, traffic collisions, and environmental impacts. Other studies combined operators' and community's interests [36], [40], [61], [66], [102], [114], [119], [120], [122], [123], [129], [131], [133], [142], [146], and the three perspectives together [39], [41], [42], [43], [44], [48], [49], [55], [57], [81], [87], [118], [132], [139], [140], [141], [143], [144], [145]. The functions itself sought to minimise uncovered/unsatisfied demand [141], passengers' travel time/cost [42], [43], [44], [48], [49], [55], [56], [81], [118], [144], staff dissatisfaction [140], minimise costs or maximise revenue [36], [55], [57], [61], [81], [87], [102], [114], [120], [122], [129], [131], [132], [133], [140], [141], [142], [143], [145], minimise energy consumption [36], [66], [114], [133], fuel consumption [120], [139], distances travelled by vehicles [118], ecological/environmental impact [81], [87], [144], and minimise emissions or maximise reduction in emissions [36], [42], [44], [48], [49], [56], [114], [118], [119], [122], [123], [129], [131], [132], [133], [140], [141], [146]. Some authors applied more specific functions as maximise car ownership and total number of trips, with user equilibrium assignment models at the lower level [40], [41], minimise social-cost (congestion and environment pollution) [43] and Gini coefficient [49], maximise environmental equity [39], social welfare [48], [61], and transportation utility [87]. As in the previous subsection, costs may represent operation [102], [132], operators' [57], [81], users' [81], [143], agency's [143], transportation/travel [48], [55], [140], vehicle [120], external [57], generalised [55], [87], [133], [145] or life cycle [36], [114], [122] costs. Also, some authors considered sustainability through emissions costs [102], [145].

At last, one important aspect is which emissions were considered in the reviewed studies. Authors have included carbon [87], [102], carbon monoxide (CO) [40], [41], [42], [43], [48], [55], [61], [118], [122], [123], [145], carbon dioxide (CO_2) [41], [55], [61], [66], [81], [122], [123], [131], [132], [137], [139], [140], [141], [142], GHG/CO_2 equivalent [36], [114], [119], [120], [129], [133], [135], [143], [144], [146], generic nitrogen oxide pollutants (NO_x) [42], [44], [49], [61], [122], [123], [132], [145], hydrocarbons (HC) [42], [61], [123], [145], methane [61], sulphur dioxide (SO_2) [122], diesel exhaust emissions [57], and particulate matter (PM [123], [132], $PM_{2.5}$ [39], [119], [122] and PM_{10} [122], [138]). More details of the studies presented in this subsection can also be found in the Appendix.

C. DEMAND AND TRAFFIC MANAGEMENT

This subsection analyses studies related to transport demand management, covering strategies to avoid and reduce unnecessary motorised travels, and, therefore, emissions, such as infrastructure and operation planning, integration with land use planning, modal integration, and traffic management. In addition, the details of the studies presented in this subsection can be verified in the Appendix.

1) URBAN PLANNING AND LAND USE

These studies have a slightly different pattern than the others, as their decision variables focused mainly on allocating land use and defining the urban densities, while the modelling of the transport system was usually included as objective functions or constraints of the problem. Also, most of the studies were explicitly aligned with transit-oriented development principles [38], [50], [59], [65], [85], [88], [91], [97], [181].

Among these studies, the most common transport mode was rail system [38], [59], [65], [85], [88], [91], [181], followed by cars [37], [45], [50], [121]. There were two multimodal studies [97], [151] and one that analysed walking [177]. Authors who have worked with land use allocation have focused on determining the type of use of a given urban land parcel [37], [38], [50], [59], [85], [88], [97], [121], [177], [181] and the densities of these parcels [38], [59], [85], [88], [97]; Hammad et al. [37] also considered the expansion of the road network and Shahraki and Turkay [121] included other transportation decision variables (average demand, route choice, average flow and capacity expansion of each network link). Other decision variables include determining the location of rail stations [65], analysing scale independence in jobs-housing and commute efficiency metrics [151], designing a sustainable urban land use and transportation system [45], and elaborating a land use and transportation development plan [91].

The studies were more interconnected than the studies in the previous subsections in terms of perspectives of passengers, operators, and community. There were similar objective functions to those subsections, such as: minimising travel costs [85], [88], [91], [151], travel times [37], [50], and the total walking distance from station to destinations [97]; minimising the total system travel time by land use allocation and path travel times [50]; maximising accessibility [65], ridership [59], [65], [85], [88], [91], [97], [181], and net suitability [177]; minimising the flow pattern (in stochastic location and route choice equilibrium) and maximising a robust risk-averse function [45]; maximising reliability probability and utility, minimising CO emission, and maximising utility value [121]. However, as already mentioned, most of the studies considered interconnected passengers', operators', and the community's interests.

As the main purpose of these studies was land use allocation, the objective functions focused on maximising land-use compactness [59], [65], [85], [88], [97], degree of mixed land use [59], [97], land value [59], overall land use status [88], economic and social value [38], and adaptability degree, and minimising the conflict degree level between the adjacent land cells or between land uses [59], [65], [85], [88], [97], costs (buildings' construction [37], connection costs of all the metro trips resulting from the developments of all the undeveloped land cells [85], land-compensation costs and road investment costs [91]), total carbon emissions from users on the traffic network [37], [121], noise pollution [37], pollution treatment and/or control costs [59], [65], [97], and environmental impacts [38], [85], [88].

2) TRAFFIC MANAGEMENT ON CONGESTED NETWORKS

There were eight studies that applied traffic management techniques and optimisation. The transport modes included cars [58], [60], [136] and multimodal networks of bicycles, buses, cars, rail, and shared mobility systems [95], of buses and cars [157], and of buses, rail systems, and cars [125]. The decision variables included network design (corridors and/or stations' location, routes) [58], [64], [95], [125], network modifications (to reverse road traffic flow or to leave it unaltered) [136], frequencies setting [95], [125], [197], fleet sizing [197], policy variables [58], [125], [157], modal split [64], and traffic management [46], [60]. For decisions on policy variables, Dantsuji et al. [157] sought to determine the level of congestion pricing for the cars and the road space required for both two modes (buses and cars), e.g., using mixed or dedicated lanes, Li et al. [58] aimed to design a toll model, and Amirgholy et al. [125] analysed different scenarios with mixed network (bus), dedicated lanes (BRT) and parallel network (metro). Traffic management strategies included traffic signal plans [60] and traffic assignment solutions [46].

Objective functions were related to minimise traffic density/volume [46], [136], [197], travel times [197], congestion cost [157], total system travel disutility and each road user's travel disutility [58], passengers', operators', and external costs [125], total passengers' travel times, construction costs, modal shift value, and balanced use value [95], travel delay, stops, fuel consumption, and integrated performance index (including CO, HC and NO_x emissions) [60], total vehicles' emissions cost [136], and to maximise traffic flow [46]. At last, as the decision variable of Feng et al. [64] was whether to implement a policy instrument (bus fare, additional private car toll, bus lane construction, and large-scale bus fleet purchase) to change the current modal split into a more sustainable one, the objective function aimed to minimise the difference between the actual and desired proportion of each mode after a combination of traffic demand management policy instruments.

D. TECHNOLOGY AND ENERGY

Optimisation techniques in technology and energy studies involved mainly energy infrastructure and operation planning, energy generation technologies, EVs, and electric buses. In total, this subsection comprises 40 articles, which details can be found in the Appendix.

Two studies analysed bike-sharing systems and personal mobility. Balacco et al. [188] sought to determine the number of docks at electric bicycle charging stations, with a charging system based on pumps used as turbine, and Kwag et al. [159] to determine the installation of wireless charging infrastructure (both static and dynamic) at tourist locations, considering electric scooters.

Bus studies focused on determining charging facility location [103], [163], [166], [167], [170], [184], [189], [198], [200] and capacity [163], routes [163], [200], bus scheduling [80], [155], [166], [167], fleet sizing [163], vehicle design [103], [163], and fleet charging schedule [108], [165], [180]. Regarding energy planning, Ifaei et al. [115] aimed at determining the best option of photovoltaic (PV) panels to be implemented on the roof of buses for the electrification of public transport, and Elkamel et al. [105] at determining the schedules of power-generating units in order to supply an electric mobility system. Studies involving rail systems focused on charging facility location [112], routes [86], rail scheduling [96], and operational aspects (acceleration, speed) [96], [111], [112].

In terms of cars, the studies sought to determine the assignments of charge stations at workplaces [113], the direction of the transfer of electricity between PV modules, battery storage, EVs, and the grid [116], charging facility location and capacity [158], [201], EVs routes [99] and charging schedule [178]. Besides allocating EVs charging stations, Gholami et al. [201] also aimed at including smart photovoltaic inverters in distribution networks. Regarding energy planning, He et al. [54] sought to determine optimal electricity prices at public charging stations for EVs and Chakrabarti et al. [130] to determine the operation of district heat networks to recharge EVs. For shared mobility systems, studies focused on charging facility location and capacity [183], charging schedule [107], [117], fleet size [107], designing the service area [126], and EV relocation plan [77], [168], [183]. As remarks, Corinaldesi et al. [162] sought to investigate the economic potential of deploying residential car sharing systems, defining tenants' investment and operation (investment decisions, PV system data, battery storage capacity), and Lamedica et al. [107] proposed a model to develop an e-mobility service for people with disabilities.

Last, Beltran et al. [149] aimed to determine the set of terminals, routes, and frequencies of green vehicles for public transport on a multimodal (buses and cars) network, besides determining the network flows. In a multimodal network with bicycles, buses, cars, and shared mobility systems, Piazza et al. [106] sought to define and design electrical services for a local energy community, which takes energy from a microgrid based on the exploitation of renewable energy sources and storage systems. Their study aimed at determining many variables, such as: the number of new PV panels; the number of new energy storage systems; the number of new EVs (cars and bikes); the number of new charging stations for EVs; the power exchanged with the distribution grid; the power produced by the PV plant; the power absorbed from/injected into the energy storage systems; the power charged to/discharged from the electric shuttle when connected to its charging system; the power charged to EVs; and the satisfied transportation demand of the EV sharing system. Brozynski and Leibowicz [128] aimed at developing an energy system for urban-scale decarbonisation, determining a climate plan with emissions, electricity generation, and private and public vehicle fuels' mixes.

Recharging facilities include stations [113], [158], [166], [170], [178], [183], [188], [189], [198], [200], [201], wireless charging infrastructure, which can be divided into static (stations) [159] and dynamic wireless charging infrastructures (roads) [103], [114], [159], and quick charger machine [184]. Renewable energy sources considered in the studies are solar [106], [108], [114], [115], [116], [128], [162] and wind [105], [128], [178].

Regarding the objective functions, most of the studies considered the operators' perspective. Nevertheless, the passengers' interests were modelled by minimising uncovered demand [188], the monetary value due to delay of all EV travellers that need recharging [158], and energy consumption [99], [162]; Qin et al. [99] considered link travel speeds and waiting times at signalised intersections in the energy consumption modelling. Chakrabarti et al. [130] included the minimisation of CO_2 emissions, considering the community's perspective. For operators' interests, the functions sought to minimise costs [54], [80], [103], [107], [108], [113], [115], [116], [117], [128], [155], [158], [159], [162], [165], [166], [167], [170], [178], [180], [189], maximise revenue [77], [105], [106], [112], [116], [126], [130], [168], [183], minimise energy consumption [86], [96], [111], [112], network losses and voltage deviation [189], [201], power losses in the distribution grid [54], [201], the number of active charging stations and the average extra stop time [198], the number of charging facilities [184], vehicle-specific-power [115], and maximise electrified vehicle mileage [163]. Passengers' and operators' interests were combined by minimising users' costs and the number of fast chargers [200]. Considering passengers', operators' and community's perspective, Beltran et al. [149] sought to minimise costs for users, operators, and externalities in a multimodal transport system. Costs may represent daily [165], annualised [113], [115], [166], or life cycle [167], investment [159], purchasing [80], [107], [113], [116], [170], construction [113], [116], [158], [170], maintenance [116], operation [80], [108], [113], [116], [117], [165], charging [107], [180], generalised [178], and travel [54], [200] costs.

E. NON-SPATIAL MEASURES

According to Aminzadegan et al. [6], economic factors as imposing fuel taxes or eliminating fuel subsidies, and converting external into internal costs would be perceived as costlier, presenting a potential to reduce emissions. However, no studies were found in line with this issue. The studies found in the literature involving non-spatial measures sought to determine which was the best investment (in modernised diesel jeepney or in e-jeepney) to a public transport system [171], develop a monetary incentive plan so a company can find the optimum commute plan for its employees, encouraging them to change their existing commute behaviour [104], design an incentive plan for passengers to switch from private to public transport service to mitigate traffic congestion and achieve sustainability [161], elaborate operational and subsidy plans for an urban rail system [69], and to determine the fare for passengers, train operation headway for operators, and an operational subsidy to the sustainable development of an urban rail system [75].

Regarding the objective functions, studies sought to maximise the value of the investment [171] and social welfare [161], and to minimise the total equivalent social cost of negative environmental impacts and total commute time [104], the difference between operating costs and income [69] and operational subsidy for flat and distance-based fare regimes [75], considering operators' and community's perspectives. More details of the studies presented in this subsection can be analysed in the Appendix.

V. ALGORITHMS AND COMMERCIAL SOLVERS

In order to solve the mathematical models of optimisation proposed by the authors mentioned in the previous section, it was used both mathematical programming-based commercial solvers and heuristics/metaheuristics. In this sense, Table 2 summarises the commonly used techniques. For studies using mathematical programming, commercial solvers as IBM CPLEX® and Gurobi® are the most frequent ones. For heuristic and metaheuristic techniques, genetic algorithms (GA) are the most employed, especially the NSGA-II (Non-dominated Sorting Genetic Algorithm II). Hybrid heuristics, simulated annealing and particle swarm-based algorithms were also found. Usually, authors have made modifications, customisations or proposed enhancements to the classic/canonical algorithm. The case that stands out the most is the NSGA-II, that was improved/modified by [42], [49], and [85]. Also, Almasi et al. [196] have compared a GA (single objective) to the NSGA-II (multi-objective). Hybrid heuristics mentioned in Table 2 comprises a combination of a hybrid GA and the adaptive destroy-and-repair algorithm [89], GA with local search [164], adaptive GA and Granular Tabu Search [82], Large Neighbourhood Search-GA [187], improved multi-objective backtracking search GA [192], hybrid tabu search - immune GA [167], variable neighbourhood search and enhanced simulated annealing algorithm [84], genetic search with advanced diversity control [95], and max–min ant system algorithm integrated with the Frank–Wolfe and Dial algorithms [91].

Focusing on implementation and modelling, Table 3 summarises the model validation metrics, the commonly used programming environments/languages, and the simulation platforms. Sensitivity analysis is the most often used way to validate the performance of the optimisation algorithms. However, other studies measure the algorithm efficiency/performance by considering the CPU time and convergence. Additionally, there were approaches that compared their techniques' behaviour with the state-of-the-art or with the classic/canonical algorithms. Less frequent validation strategies were made by comparing the proposed

TABLE 2. Optimisation techniques commonly used in the state-of-the-art articles.

Techniques	No. of articles	References
CPLEX®	22	[73, 84, 98, 103, 108, 119, 126, 131, 133, 140, 141] [151, 155, 158, 159, 163, 165, 168, 177, 180, 185, 199]
Gurobi®	11	[39, 72, 92, 106, 109, 146, 160, 162, 166, 170, 174]
Branch-and-bound / branch-and-price	4	[62, 101, 109, 150]
Column generation	2	[101, 184]
Simplex method	2	[43, 181]
Monte Carlo	2	[58, 134]
GA	30	[36, 38, 40, 46, 48, 56, 59, 60, 65, 71, 77–81, 88, 93, 97, 102] [110–112, 120, 148, 149, 159, 172, 175, 188, 196]
NSGA-II	12	[42, 85, 115, 120, 129, 136, 142, 144, 189, 190, 196, 198]
Hybrid heuristics	10	[74, 82, 84, 89, 91, 95, 164, 167, 187, 192]
Simulated annealing	6	[45, 51, 63, 67, 69, 158]
Particle swarm-based algorithms	5	[55, 66, 139, 191, 200]

techniques with commercial solvers and by comparing the model results to real data. In terms of programming environment/language, MATLAB, Python, GAMS (General Algebraic Modelling System) and AMPL (A Mathematical Programming Language) were the most used. It is important to mention that MATLAB is still the most used due to the integration in the same environment of the optimisation technique and the mathematical model with the execution of simulations of dynamical systems. Moreover, there are authors that integrate traffic simulators and GIS (Geographic Information System) softwares mainly with Python.

VI. FUTURE DIRECTIONS

Although there were some studies that directed their efforts to investigate the social aspects of the transport sector, few solutions considered these aspects in the optimisation field, which focus relied mostly on operational aspects. Therefore, some research opportunities rely on expanding the modelling of optimisation problems including the analysis of benefits generated for the community and/or considering the perspectives of passengers, operators, and the community simultaneously. This can be addressed, for example, by designing equitable operation systems to maximise the overall benefits, considering benefits of public transport and bike-sharing systems on reducing trips made by cars, assessing traffic accidents and human health impacts, and analysing general improvements in the quality of city life and the urban environment, while also considering operational aspects. To reduce existing urban inequalities, special attention should be devoted to traditionally disadvantaged communities.

Related to each mode of transport, there are few studies on cycling networks and on electric bicycles in bike-shared systems, its operation and system deployment. For public transport, especially buses, a large body of studies already exists, but it is still possible to explore aspects of sustainability within systems, expanding and incorporating mainly the community perspective into analyses, since passengers' interests (e.g. travel times) and operators' interests (e.g. costs and revenue) are widely documented. It is also possible to explore power supply sources for electrical systems, or alternative priority infrastructure schemes, such as dynamic or intermittent bus lanes. For cars and shared-systems, analysing the impact of EVs penetration on the grid should continue to be a research trend. Henceforth, much remains to be investigated in terms of restricted parking zones, roads with reduced speed, different congestion pricing schemes, and integration of MaaS strategies with "traditional" transport systems, for example, integration between bike-sharing systems and public transport, and the impact of such measures on GHG emissions and climate change.

Another area for contributions concerns creating models to integrate different modes of transport and integrating transport systems and land use planning, or improving current ones. There are several future research directions to answer open questions. One of those is including trip distribution, mode choice and traffic assignment problems into the optimisation. As presented in section IV, so far this was done by multi level formulations. Future studies may include or improve travel choice behaviour, mode choice, modal shift patterns, modal split, dynamic traffic assignment, and other behavioural models for travellers' route choice into the optimisation models; the impacts of psychological / soft measures in modal shift patterns could also be included and further investigated. The unanswered questions also may be addressed by designing multimodal networks, developing trip distribution, modal split, and trip assignment problems considering the land use effect, and investigating the extent to which changes in density and land use mixture would affect transit share, trip length distribution, vehicle emission, and pollution rates.

Another direction is including or expanding demand models in the mathematical formulation of optimisation problems, with demand anticipation models, dynamic/time-varying demand, induced demand, uncertain demand, potential demand, demand changing factors, and estimating the distribution of passenger flow using sensor data, such as cellular signalling data, for example. It is also possible to address demand modelling by predicting the behaviour of passengers, incorporating personal preferences, accounting behavioural difference of heterogeneous users, incorporating psychological factors into travel demand models, and by analysing external influence (e.g. weather conditions) on demand.

TABLE 3. Implementation and modelling aspects.

Aspects	Specification	No. of articles	References
Validation	Algorithm efficiency or performance (CPU time, convergence, etc)	29	[43, 46, 48, 52, 60, 62, 69, 79, 104, 117, 126] [127, 132, 135–137, 147, 151, 152, 158] [154, 168, 178, 179, 187, 193, 199–201]
	Comparison of solution approach to literature solution methods	23	[37, 42, 55–57, 82, 84, 87, 89, 95–97, 100, 101] [110, 160, 172, 189, 191, 192, 194, 195, 197]
	Comparison of solution approach to commercial solvers	5	[63, 81, 140, 155, 180]
	Comparison of model results and real data	5	[41, 70, 86, 100, 118]
	Model efficiency	2	[93, 175]
	Sensitivity analysis	67	[36, 45, 47, 52, 53, 58, 64, 67, 69, 72] [74, 75, 77, 80, 82, 87, 88, 92, 94, 95, 98, 99] [104, 106, 108, 111–115, 117, 119, 121] [124–126, 128, 129, 133–135, 139–142, 144] [145, 148–150, 157, 163–168, 171, 173] [183–186, 190, 191, 196, 200]
Programming language	AMPL	4	[37, 93, 113, 168]
	GAMS	11	[44, 103, 105, 121, 125, 130–133, 163, 178]
	MATLAB	37	[36, 40, 41, 52, 54, 55, 59, 62, 64–66, 71, 73] [82, 87, 89, 93, 95, 96, 99, 106, 107, 111, 112] [114, 116, 138, 147, 148, 164, 171, 182, 187] [191, 196, 198, 201]
	Python	18	[37, 68, 80, 83, 86, 91, 92, 94, 98, 101] [136, 160, 162, 172, 173, 192, 199, 200]
Simulation platforms	GIS	3	[104, 152, 156]
	Traffic simulators (Aimsun, MATSim, Paramics, SUMO, VISSIM)	10	[60, 70, 83, 94, 124, 137, 139, 157, 190, 197]

Besides demand aspects, sources of uncertainty should be considered in future studies. Uncertainty may be considered in travel times, network, parameters, demand, and energy consumption rates. Traffic conditions may also represent a source of uncertainty. Even though some studies are already investigating congested networks, the trend of increasing congestion keeps this as a direction of future studies, which can be addressed by considering advanced traffic prediction techniques, more extensive approaches for traffic inputs, such as real time traffic conditions and interaction between mixed traffic.

Regarding technology and energy, there are gaps concerning vehicles and fuels, as further analysing environment-friendly alternative fuels, hybrid and electric vehicles, and evaluating the impact of a transition towards hybrid and electric vehicles for private and public transportation, especially regarding the depletion of non-renewable resources. The research gaps can be addressed by further analysing these technological innovations, improving fuel efficiency, environmental benefits, and air quality. One future direction includes improving operational aspects of EVs, as the size and operation of energy storage systems and the impact of charging types on the energy storage lifespan of the vehicles. Also, there are unanswered questions regarding the impact of digitalisation itself of transport systems, i.e. how the insertion of technology — rather than vehicle technology — can be used for reducing the consumption of energy in transportation.

Another possibility of contribution concerns the integration of transport and energy planning, which is still limited so far. Research opportunities regard integrating the network operational demand and the power generation and distribution systems, creating more realistic energy consumption models, including detailed manufacturer's information, analysing the impact of EVs on the grid, and further investigating different charging methods. Energy modelling can also be enhanced by including a more detailed scheduling of charging schemes to capture the effects of electricity consumption rate fluctuating during the day, dynamic energy consumption models, and dynamic charging policies. It is also possible to expand the optimisation studies of the energy systems that supply the mobility systems, investigating alternative energy-saving schemes and the impact of different renewable energy sources, and also introducing

TABLE 4. Planning and policy-making studies.

Paper	Transport mode	Decision variables	Objective functions	Solution approach	Model validation
Sayarshad et al. (2012) [150]	Bike-sharing	Fleet management	Maximise company's benefit	Branch and bound approach	Yes
Frade and Ribeiro (2015) [153]	Bike-sharing	Network design (station capacity) and fleet sizing	Maximise covered demand	-	No
Hu et al. (2019) [174]	Bike-sharing	Network design (station location and capacity)	Minimise uncovered demand	Gurobi	No
Zhang et al. (2019) [134]	Bike-sharing	Network design (station capacity) and fleet sizing and management	Minimise design and operation costs	Monte Carlo method	Yes
Lahoorpoor et al. (2019) [175]	Bike-sharing	Fleet management	Minimise rebalancing vehicle mileage	Genetic algorithm	Yes
Wu et al. (2019) [179]	Bike-sharing	Fleet management	Maximise daily profit	Ranking and selection (R&S) method	Yes
Yang et al. (2020) [78]	Bike-sharing	Network design (station location)	Maximise covered demand and minimise distance to a bike station	Genetic algorithm	No
Muren et al. (2020) [73]	Bike-sharing	Network design (station location) and fleet sizing and management	Maximise covered demand, minimise workload, and minimise transport distance	CPLEX	No
Soriguera and Jiménez-Meroño (2020) [186]	Bike-sharing	Network design (station location and capacity) and fleet management	Minimise generalised costs	Continuous approximations	Yes
Fan et al. (2020) [182]	Bike-sharing	Fleet sizing and management	Maximise profit and minimise rebalancing costs	Mean value analysis (MVA) algorithm; Flow equivalent server (FES)	No
Jia et al. (2020) [191]	Bike-sharing	Fleet management	Minimise travelled distance, and maximise rebalancing utility	Multistart multi-objective particle swarm optimisation (MS-MOPSO)	Yes
Luo et al. (2020) [72]	Bike-sharing	Fleet management	Minimise rebalancing vehicle mileage	Gurobi	Yes
Askarzadeh and Bridgelall (2021) [156]	Bike-sharing	Network design (station location)	Minimise distance in the network	Location-allocation optimisation model in a GIS platform	No
Chang et al. (2021) [84]	Bike-sharing	Fleet management	Minimise generalised costs	Hybrid metaheuristic algorithm that incorporates variable neighbourhood search (VNS) and enhanced simulated annealing (ESA) algorithm	Yes
Zhang et al. (2021) [82]	Bike-sharing	Fleet management	Minimise vehicle's transportation time and passengers' waiting time	Hybridisation of adaptative genetic algorithm (AGA) and Granular tabu search (GTS)	Yes
Qian et al. (2022) [148]	Bike-sharing	Network design (station location)	Maximise accessibility and annual revenue	Genetic algorithm	Yes
Fu et al. (2022) [98]	Bike-sharing	Network design (station location and capacity) and fleet management	Maximise revenue	Row generation approach; algorithm proposed by the authors	Yes
Cao and Xu (2022) [192]	Bike-sharing	Fleet management	Minimise rebalancing amount and costs	Improved multi-objective backtracking search genetic algorithm (IMBSGA)	Yes
Zhou et al. (2022) [101]	Bike-sharing	Fleet management	Minimise transportation costs	Algorithm proposed by the authors (based on column generation and branch-and-price algorithm)	Yes
Ceder et al. (2015) [199]	Bus	Network design (station location)	Minimises operation costs and user access costs	Evolutionary Algorithm and CPLEX	Yes
Ma et al. (2016) [147]	Bus	Service area	Maximise accessibility	Algorithm branch sprouting (ABS), Algorithm branch pruning (ABP), Algorithm merge-cluster (AMC), Algorithm tree grafting (ATG)	Yes
Wu et al. (2016) [124]	Bus	Operational aspects (dwell time, speed)	Minimise bus operational costs (delay, stops, acceleration)	Algorithm proposed by the authors (pseudo-code presented)	Yes
Liu et al. (2017) [62]	Bus	Bus scheduling	Maximise ridership	Branch and bound approach	Yes
Nesheli et al. (2017) [127]	Bus	Operational aspects (vehicle holding/boarding time, vehicle skipping stops)	Minimise total passengers' travel time and maximise direct transfers	ILOG	Yes
Liu and Ceder (2017) [169]	Bus	Bus scheduling	Minimise total passengers' travel time, passenger load discrepancy and fleet size	Deficit function (DF)–based sequential search	No
Ceylan and Ozcan (2018) [193]	Bus	Frequencies setting and timetable development	Minimise total passengers' travel time and vehicle mileage	Metaheuristic harmony search (HS)	Yes
Ruano-Daza et al. (2018) [194]	Bus	Network design (routes) and frequencies setting	Minimise passengers' travel time and operation costs	Multi-objective global-best harmony search (MOGBHS)	Yes
Gong et al. (2019) [67]	Bus	Bus scheduling	Minimise passenger travel cost and operation costs	Simulated annealing algorithm	Yes
Jia et al. (2019) [68]	Bus	Network design (routes)	Minimise total passengers' travel time	Algorithm proposed by the authors (pseudo-code presented; includes the shortest path)	No
Peña et al. (2019) [110]	Bus	Bus scheduling	Minimise operation costs and unsatisfied user demand	Multi-objective Cellular genetic algorithm	Yes
Ren et al. (2020) [74]	Bus	Network design (station location and routes)	Minimise vehicle mileage	*VrpPd* software (adaptive large neighbourhood search with simulated annealing); pseudo-code presented	Yes

TABLE 4. ***(Continued.)*** **Planning and policy-making studies.**

Rinaldi et al. (2020) [185]	Bus	Bus scheduling	Minimise operation costs	Decomposition scheme; CPLEX	Yes
Yang and Liu (2020) [79]	Bus	Frequencies setting and bus scheduling	Minimise passengers' waiting time and vehicle energy consumption	Two-phase algorithm (genetic algorithm / subjective weighting using multi-criteria analysis)	Yes
Wang et al. (2021) [76]	Bus	Network design (station location and routes)	Maximise ridership	Heuristic method	No
Sun et al. (2021) [89]	Bus	Network design (routes) and bus scheduling	Minimise operator costs and passengers in-vehicle cost	Heuristic algorithm integrating a hybrid genetic algorithm (HGA) and the adaptive destroy-and-repair (ADAR) method	Yes
Tang et al. (2021) [90]	Bus	Network design (routes)	Minimise passengers' travel time	Network-based algorithm (pseudo-code presented; includes the shortest path)	No
Guan et al. (2022) [187]	Bus	Network design (routes) and bus scheduling	Minimise vehicle mileage	LNS-Genetic algorithm	Yes
Jiang (2022) [53]	Bus	Frequencies setting	Maximise the network fairness and minimise travel costs	Artificial bee colony algorithm	Yes
Lin and Hsieh (2022) [195]	Bus	Network design (routes)	Maximise profit and minimise construction and maintenance costs	Multi-source bidirectional Gaussian-prioritised spanning tree (BiasSpan)	Yes
Lu et al. (2022) [164]	Bus	Network design (routes), frequencies setting, and fleet sizing	Minimise operation costs	Hybrid genetic algorithm with a local search	Yes
Mera and Balijepalli (2020) [51]	Car	Road management	Minimise vulnerability and individual travel time	Simulated annealing based algorithm	No
Luo and Yang (2021) [160]	Car	Road management	Minimise total time cost	Gurobi	Yes
Bi et al. (2021) [83]	Car	Road management	Minimise user's rewarding costs	CVXPY	No
Bi et al. (2022) [94]	Car	Traffic management	Minimise user's rewarding costs	Algorithm proposed by the authors (pseudo-code presented)	Yes
Ye et al. (2021) [52]	Multimodal	Network design (station location and capacity)	Maximise the total number of trips generated and minimise stochastic user equilibrium functions	Successive linear programming (SLP)	Yes
Khoo et al. (2014) [190]	Multimodal (bus, car)	Network design (corridor location)	Minimise the average travel time	Microscopic traffic simulation and NSGA-II	Yes
Li et al. (2016) [47]	Multimodal (bus, car)	Bus scheduling and fuel surcharges	Maximise the total social net benefit	Heuristic algorithm (based on Hooke–Jeeves approach)	Yes
Haitao et al. (2019) [173]	Multimodal (bus, car)	Network design (corridor location)	Maximise the average passenger flow	Proportional-integral-derivative (PID) controllers	Yes
Gao et al. (2020) [70]	Multimodal (bus, car)	Traffic management	Minimise intersection delay	Algorithm proposed by the authors (pseudo-code presented; includes simulation)	Yes
Marseglia et al. (2019) [176]	Multimodal (bus, rail)	Network design (corridor location)	Maximise covered demand	Heuristic GreCon (greedy constructive insertion of edges)	No
Almasi et al. (2021) [196]	Multimodal (bus, rail)	Network design (routes), frequencies setting, and operational aspects (dwell time)	Minimise passenger costs, operator costs and unsatisfied demand costs	Genetic algorithms and NSGA-II	Yes
Wang et al. (2021) [92]	Multimodal (rail, shared mobility)	Network design (station location)	Maximise vehicle mileage savings	Gurobi	Yes
Kang et al. (2014) [152]	Rail	Network design (corridor location)	Minimise generalised costs	A genetic and GIS-based algorithm	Yes
Chen et al. (2016) [154]	Rail	Network design (station location and routes)	Minimise travel costs	Genetic algorithm	Yes
Yue et al. (2017) [63]	Rail	Timetable development and rail scheduling	Minimise passengers' waiting time, operation costs, and train infeasibility	Simulated annealing algorithm	Yes
Garrisi and Cervelló-Pastor (2019) [172]	Rail	Timetable development	Minimise train delay	Genetic algorithm; Gurobi	Yes
Hou et al. (2020) [71]	Rail	Evacuation plan for rail transit line emergency	Maximise the total number of stranded passengers transferred	Genetic algorithm	No
Zhou et al. (2021) [93]	Rail	Frequencies setting and operational aspects (stop scheme and operation time)	Minimise total passengers' travel time	Genetic algorithm	Yes
Zhao et al. (2022) [100]	Rail	Rail scheduling and fleet management	Minimise operation costs	Two-stage approach (pseudo-code presented)	Yes
Murray and Feng (2016) [109]	Walking	Network design (public lightning location)	Minimise costs	Branch and bound approach / Gurobi	No

new balancing alternatives to the grid. Finally, it may be possible to improve current models into more realistic ones by implementing pilot projects of some technologies. These pilot projects could provide real data for improving optimisation modelling.

The analysis of environmental impacts and emissions can be further improved, as in the current studies they generally appear as secondary objectives or have little emphasis. This gap can be addressed by expanding the evaluation of the environmental impacts of the proposed technologies and systems, creating more sophisticated emission models, incorporating other pollutants besides CO_2 and, consequently, analysing not only the environmental but also human health impacts and considering pollutant emissions from different modes of

TABLE 5. Environmental variables studies.

Paper	Transport mode	Emissions	Decision variables	Objective functions	Solution approach	Model validation
Gámez-Pérez et al. (2019) [131]	Bike-sharing	CO_2	Network design (station location)	Minimise costs and maximise annual reduction in CO_2 emissions	ϵ-constraint method	No
Wu et al. (2023) [102]	Bike-sharing	Carbon	Fleet management	Minimise operation costs and carbon emission costs	Genetic algorithm	No
Jánošíková et al. (2012) [118]	Bus	CO	Network design (routes), frequencies setting	Minimise passengers' travel time, kilometres ridden by all vehicles, and the total amount of emissions	Tchebycheff-norm scalarization	Yes
Gouge et al. (2013) [119]	Bus	CO_2 equivalent, $PM_{2.5}$	Bus scheduling	Minimise global warming commitment, $PM_{2.5}$ and the total emissions	CPLEX	Yes
Ribau et al. (2014) [120]	Bus	CO_2 equivalent	Vehicle design	Minimise vehicle cost, fuel consumption, and life cycle CO_2 emissions	Genetic algorithm and NSGA-II	No
Ercan et al. (2015) [122]	Bus	CO, SO_2, NO_x, PM_{10}, and $PM_{2.5}$, CO_2	Bus fleet composition	Minimise life cycle costs and emissions	Simplex	No
Jiménez and Román (2016) [123]	Bus	CO_2, CO, THC, NO_x and PM	Fleet assignment	Minimise emissions	CPLEX	No
Bi et al. (2018) [36]	Bus	GHG / CO_2 equivalent	Network design (charging facility location)	Minimise life cycle costs and GHG emissions; minimise life cycle costs and energy consumption	Genetic algorithm	Yes
Ribau et al. (2018) [129]	Bus	CO_2 equivalent	Vehicle design	Minimise life cycle CO_2 emissions and maximise financial aspects	NSGA-II and spherical pruning multi-objective differential evolution algorithm (spMODE-II)	Yes
Duran et al. (2019) [56]	Bus	CO_2	Network design (routes), frequencies setting	Minimise total travel time and CO_2 emissions	Multi-objective genetic algorithm (MGA)	Yes
Xylia et al. (2019) [133]	Bus	GHG / CO_2 equivalent	Network design (charging facility location)	Minimise generalised costs, energy consumption, and annual emissions	CPLEX	Yes
Sun and Apland (2019) [132]	Bus	CO_2, NO_X, PM	Bus scheduling	Minimise operating costs, time- and zone-specific performance criteria, and emission levels	OSICPLEX	Yes
Zhang et al. (2020) [81]	Bus	CO_2	Fleet procurement and sizing, frequencies setting, scheduling	Minimise operator's cost and passengers' waiting time cost	Genetic algorithm	Yes
Sadeghi et al. (2021) [57]	Bus	Diesel exhaust emissions	Network design (routes), frequencies setting	Minimise operator and external costs	Cuckoo search algorithm	Yes
Zhou et al. (2021) [39]	Bus	$PM_{2.5}$	Network design (charging facility location)	Maximise environmental equity	Gurobi	No
Kolak et al. (2013) [44]	Car	NO_x	Traffic management	Minimise total emission and travel times	NLPEC	No
Sun et al. (2016) [48]	Car	CO	Toll placement	Maximise total social welfare and equity, and minimise CO emissions and travel costs	Genetic algorithm	Yes
Kolak et al. (2018) [49]	Car	NO_x	Traffic management	Minimise total emission, Gini coefficient, and travel times	Self-regulated averaging (SRA) and adapted NSGA-II	No
Bi et al. (2019) [114]	Car	Multiple GHG pollutants / CO_2 equivalent	Network design (road segment deployment)	Minimise life cycle costs, GHG emissions, and energy	Genetic algorithm	Yes
Nguyen and Jung (2021) [139]	Car	CO_2	Traffic management	Minimise fuel consumption	Algorithm based on ants' swarm intelligence	Yes
Abudayyeh et al. (2021) [137]	Car	CO_2	Traffic signal plan	Minimise the travel time and CO2 emissions	Cross-entropy method	Yes
Si et al. (2012) [43]	Multimodal (bicycle, bus, car)	CO	Policy variables	Minimise social-cost (congestion and environment pollution) and users' generalised travel cost	Algorithm proposed by the authors (pseudo-code presented)	Yes
Meng et al. (2016) [55]	Multimodal (bicycle, bus, car)	CO, CO_2	Multimodal traffic assignment	Minimises generalised travel costs	Particle swarm optimisation	Yes
Li and Lu (2021) [87]	Multimodal (bicycle, bus, rail, car)	Carbon	Urban passenger traffic structure	Maximise transportation utility, and minimise ecological impact and generalised cost	Ideal point method, linear weighting method, and layered sequence method	Yes
Doorley et al. (2020) [135]	Multimodal (bicycle, car)	GHG / CO_2 equivalent	Network design (cycling lanes deployment)	Maximise societal benefit	Genetic algorithm	Yes
Yang et al. (2008) [41]	Multimodal (bus, car)	CO, CO_2	Car ownership and link flow	Maximise zonal car numbers and minimise travel times	Sensitivity analysis based algorithm	Yes
Sharma and Mathew (2011) [42]	Multimodal (bus, car)	NO_x, CO, and HC	Network design (road segment deployment)	Minimises travel times and total emissions	An improved version of NSGA-II	Yes
Ye et al. (2022) [146]	Multimodal (bus, car)	GHG / CO_2 equivalent	Network design (charging facility location)	Minimises GHG emissions	Gurobi	No
Asghari et al. (2022) [140]	Multimodal (bus, car, shared mobility)	CO_2	Network design (routes)	Minimise total transportation costs, staff dissatisfaction, and total carbon emissions	Algorithm based on Pareto strength ant colony optimisation (PSACO)	Yes

TABLE 5. ***(Continued.)*** **Environmental variables studies.**

Griswold et al. (2014) [143]	Multimodal (bus, rail)	GHG / CO_2 equivalent	Network design (station location and routes), frequencies setting	Minimise user and agency costs	-	No
Qin and Zhang (2015) [61]	Multimodal (bus, rail)	CO_2, CO, NO_x and CH	Policy variables	Maximise social welfare and operators' profit	Standard backward approach	No
Yang et al. (2022) [145]	Multimodal (bus, rail)	CO, NO_x, and HC	Network design (station location and routes), frequencies setting	Minimise hourly generalised cost (user, operator, and emission costs)	Successive substitution solution approach	Yes
Feng et al. (2008) [40]	Multimodal (car, other modes)	CO	Car ownership and number of trips	Maximise car ownership and total number of trips by car and non-car modes, and minimise combined trip distribution and assignment model	Genetic algorithm	No
Qiang et al. (2018) [66]	Multimodal (walking, bicycle, bus, rail, car)	CO_2	Urban passenger traffic structure	Minimise energy consumption	Artificial fish swarm algorithm (AFSA)	No
Loy-Benitez et al. (2021) [138]	Rail	PM_{10}	Ventilation control system	Minimise indoor PM_{10} concentration and ventilation energy consumption	Multi-objective harmony search (MOHS)	No
Khathawatcharakun and Limsawasd (2022) [144]	Rail	GHG / CO_2 equivalent	Network design (station location)	Minimise passengers' travel time and environmental impact	NSGA-II	Yes
Aydin et al. (2022) [141]	Shared mobility	CO_2	Network design (station location)	Minimise costs, CO_2 emissions, and unsatisfied demand	Lexicographic weighted Tchebycheff method	Yes
Gandomani et al. (2022) [142]	Shared mobility	CO_2	Network design (routes), scheduling, fleet sizing	Minimise costs	NSGA-II	Yes

transportation in urban transport systems. The resilience of urban transport networks can also be better integrated into optimisation models.

Other research opportunities are related to the expansion of studies involving life cycle cost analysis, investigating the long-term environmental impacts and emissions, making the proposed systems more sustainable in the context of climate emergency. This analysis would shed light on the discussion of where to direct our efforts towards a fair and sustainable transition on energy and mobility systems. Few studies were found in the area of economic studies and non-spatial measures. Despite being difficult to indicate a research trend, it is possible to point out that more studies are needed in terms of fuel and energy transition economical incentives, financing of public transport and active transport systems, such as subsidy schemes to cheapen transport fares as a measure of mode shift. Also, contributions can be made regarding the demand impact of fare integration within different modes, systems, and operators. The conflict between different operators / stakeholders regarding the share of revenue within MaaS services remains not addressed in the optimisation literature field.

Other enhancements can be achieved to push the transport optimisation area further, for example, by formulating and solving more complex multi-objective or bi-level optimisation problems, incorporating online control algorithms into the proposed models, exploring hybrid algorithms for improving both computation efficiency and solution quality, and comparing the optimisation results of different heuristic algorithms. As a final remark, the problem of model/network complexity persists, i.e. more complex models are usually applied in theoretical networks, lacking real applications. On the other hand, models applied in real networks tend to be more simplified. Thus, problems related to large-scale networks continue to have modelling, solution, and computational difficulties. Future research directions include handling large-scale network problems and extending the models to more complex transport networks, such as the multimodal networks mentioned above and metropolitan areas' networks, which have several modes and operators.

VII. CONCLUSION

This survey described the trends in the field of sustainable urban mobility optimisation, considering passenger transportation. Besides updating previous surveys/reviews that focused on transport network planning, this survey synthesised information on how optimisation techniques may contribute to promote more sustainable transport modes, decarbonisation of the sector, and reduction of GHG emissions.

Several modelling aspects were shown, such as sustainability aspects (economical, environmental, and social), the nature of objective functions, the interests considered in the modelling, and the network application. Around half of the studies explicitly considered sustainability in the modelling, but most of them addressed only the environmental aspect of it. Also, most of the mathematical formulations were done with single objective functions and considering the operators' perspective. From that, it was possible to suggest that future research could be more focused on social aspects of transport optimisation, with more complex models (multi-level and/or multi-objective), and take into consideration the interests of passengers, operators, and the community simultaneously. Although most of the studies were applied in real networks, handling large-scale networks remains one problem to be addressed in the future.

Most of the studies focused on planning the transport networks (bike-sharing, bus and rail systems, multimodal networks) by defining infrastructure and/or operation aspects as location of stations, corridors, routes, frequencies, and vehicle scheduling. Concerning sustainability, the studies

TABLE 6. Demand and traffic management studies.

Paper	Transport mode	Decision variables	Objective functions	Solution approach	Model validation
Li et al. (2012) [58]	Car	Network design (routes) and policy variables	Minimise total system travel disutility and each road user's travel disutility	Sample average approximation (SAA)	Yes
Li et al. (2014) [45]	Car	Urban land use and transportation system	Minimise flow pattern and maximise a robust risk-averse function	Sample average approximation (SAA); simulated annealing	Yes
Ma et al. (2014) [60]	Car	Traffic management	Minimise travel delay, stops, fuel consumption, and integrated performance index (including CO, HC and NO_x emissions)	Genetic algorithm	Yes
Shahraki and Turkay (2014) [121]	Car	Housing allocation and network design (link flow and capacity)	Maximise reliability probability and utility, minimise CO emission, and maximise utility value	ϵ-constraint method	Yes
Huang et al. (2015) [46]	Car	Traffic management	Maximise traffic flow and minimise the traffic volume	Genetic algorithm	Yes
Hammad et al. (2019) [37]	Car	Land use (allocation), road network expansion	Minimise noise pollution, buildings' construction costs, total carbon emissions from users on the traffic network, and individual travel times	Lexicographic optimisation algorithm; CPLEX	Yes
Lin and Zhang (2020) [50]	Car	Land use (allocation)	Minimise the total system travel time by land use allocation and path travel times	Dirichlet allocation algorithm, a simulation-based heuristic algorithm	No
Salman and Alaswad (2020) [136]	Car	Network modifications (to reverse road traffic flow or to leave it unaltered)	Minimises maximum traffic density and total vehicles' emissions cost	NSGA-II	Yes
Niedzielski et al. (2013) [151]	Multimodal	-	Minimise travel costs	CPLEX	Yes
Cai et al. (2022) [95]	Multimodal (bicycle, bus, rail, car, shared mobility)	Network design (station location and routes), frequencies setting	Minimise total passengers' travel times, construction costs, modal shift value, balanced use value	Hybrid genetic search with advanced diversity control (HGSADC)	Yes
Armas et al. (2018) [197]	Multimodal (bus, car)	Frequencies setting, fleet sizing	Minimise traffic density and travel times	ϵ-Sampling and v-Hood (AϵSvH) algorithm	Yes
Feng et al. (2018) [64]	Multimodal (bus, car)	Modal split	Minimise the difference between the actual and targeted proportion of each transport mode after a combination of TDM policy instruments are implemented	Algorithm proposed by the authors (pseudo-code presented)	Yes
Dantsuji et al. (2021) [157]	Multimodal (bus, car)	Network design (corridor location), policy variables	Minimise congestion cost	Algorithm proposed by the authors (pseudo-code presented)	Yes
Amirgholy et al. (2017) [125]	Multimodal (bus, rail, car)	Network design (routes), frequencies setting, policy variables	Minimise passengers, operator, and external costs	GAMS/Baron	Yes
Dong et al. (2022) [97]	Multimodal (rail, car)	Land use (allocation and density)	Maximise ridership, land-use compactness, and degree of mixed land use, and minimise conflict level between different adjacent land parcels, the pollution treatment cost, and the total walking distance from station to destinations	Improved NSGA-III	Yes
Li et al. (2010) [59]	Rail	Land use (allocation and density)	Maximise ridership, land-use compactness, degree of mixed land use, and land value, and minimise conflict level between adjacent land use and the cost of pollution control	Two phases / parallel genetic algorithm	No
Ma et al. (2018) [65]	Rail	Network design (station location)	Maximise ridership, land-use compactness and accessibility, and conflict degree between adjacent land uses and the cost of pollution control	Immune genetic algorithm (IGA)	No
Berawi et al. (2020) [181]	Rail	Land use (allocation)	Maximise ridership	Simplex method	No
Liu et al. (2020) [38]	Rail	Land use (allocation and density)	Maximise economic and social value, and minimise environmental impacts	Genetic algorithm	No
Feng et al. (2021) [85]	Rail	Land use (allocation and density)	Maximise ridership and the land-use compactness, and minimise connection costs of all the metro trips resulting from the developments of all the undeveloped land cells, the total time cost, conflict degree level between the adjacent land cells, negative environmental impacts	Improved NSGA-II	No
Ruan et al. (2021) [88]	Rail	Land use (allocation and density)	Maximise ridership, land use compactness, overall land use status, and minimise total road travel time, conflict level between different land types in adjacent cells, and negative environmental impacts	Immune genetic algorithm (IGA)	Yes
Xu and Yan (2021) [91]	Rail	Urban land use and transportation system	Minimise land-compensation costs, road investment costs, passengers' travel time, and maximise adaptability degree and ridership	Max–min ant system (MMAS) algorithm integrated with the Frank–Wolfe and Dial algorithms	No
Sinha and Griffith (2019) [177]	Walking	Land use (allocation)	Maximise net suitability	CPLEX	No

that included environmental objectives and the pollutants were detailed, while demand and traffic management covered studies that integrated urban planning and land use to transport planning, and congested networks analysis. Technological enhancements as EVs and energy planning were also presented, covering the type of recharging facilities and systems and the renewable energy sources found. Lastly, non-spatial measures covered only a few articles discussing

TABLE 7. Technology and energy studies.

Paper	Transport mode	Decision variables	Objective functions	Solution approach	Model validation
Balacco et al. (2021) [188]	Bike-sharing	Network design (charging facility capacity)	Minimise uncovered demand	Genetic algorithm	No
Kwag et al. (2021) [159]	Bike-sharing	Network design (charging facility location)	Minimise investment costs	Genetic algorithm	No
Huang and Li (2016) [155]	Bus	Bus scheduling	Minimise costs	Label-correcting algorithm	Yes
Sebastiani et al. (2016) [198]	Bus	Network design (charging facility location)	Minimise the number of active charging stations and the average extra stop time	NSGA-II	No
Liu and Song (2017) [103]	Bus	Network design (charging facility location), vehicle design	Minimises the total cost of batteries and charging facilities	CPLEX	No
Wei et al. (2018) [170]	Bus	Network design (charging facility location)	Minimise vehicle purchasing and charging stations' construction costs	Gurobi	No
Iliopoulou et al. (2019) [200]	Bus	Network design (routes, charging facility location)	Minimises passengers' costs and the number of fast chargers	Multi-objective particle swarm optimisation (MOPSO)	Yes
Abdelwahed et al. (2020) [180]	Bus	Charging schedule	Minimise charging costs	CPLEX	Yes
Ifaei et al. (2020) [115]	Bus	Energy network technology	Minimise the total annualised cost of the PVs and vehicle-specific-power	NSGA-II	Yes
Moon et al. (2020) [184]	Bus	Network design (charging facility location)	Minimise the number of charging facilities	Column generation techniques	Yes
Yao et al. (2020) [80]	Bus	Bus scheduling	Minimise vehicle purchasing and operation costs	Genetic algorithm	Yes
Elkamel et al. (2021) [105]	Bus	Power generating schedule	Maximise profit	Bender's decomposition and Integer L-shaped method	No
Gairola and Nezamuddin (2022) [163]	Bus	Network design (routes, and charging facility location and capacity), fleet sizing, vehicle design	Maximise electrified vehicle mileage	CPLEX	Yes
Manzolli et al. (2022) [165]	Bus	Charging schedule	Minimise daily operation costs	CPLEX	Yes
Wang et al. (2022) [166]	Bus	Network design (charging facility location), bus scheduling	Minimise annualised costs	Gurobi	Yes
Wang et al. (2022) [167]	Bus	Network design (charging facility location), bus scheduling	Minimise lifecycle costs	Hybrid TS-IGA (tabu search - immune genetic algorithm) algorithm	Yes
Zaneti et al. (2022) [108]	Bus	Charging schedule	Minimise operation costs	Dynamic approach based on a rolling horizon method	Yes
Zhang et al. (2022) [189]	Bus	Network design (charging facility location)	Maximise traffic flow and minimise the total cost; minimise network losses and voltage deviation	NSGA-II	Yes
Huang and Zhou (2015) [113]	Car	Charging schedule	Minimise annualised purchasing, construction, and operation costs	CPLEX	Yes
He et al. (2016) [54]	Car	Energy price	Minimise power losses in the distribution grid and total travel cost	SID-PSM algorithm (pattern search method)	No
Chakrabarti et al. (2019) [130]	Car	Power generating schedule	Maximise annual profit; minimise CO_2 emissions	The modelling tool GAMS	No
Tayarani et al. (2019) [178]	Car	Charging schedule	Minimise generalised costs	Conopt-4	Yes
Mercan et al. (2020) [116]	Car	Energy management	Minimise purchasing, construction, maintenance, and operation costs, and maximise total revenue	Rule-based decision-making	No
Kavianipour et al. (2021) [158]	Car	Network design (charging facility location and capacity)	Minimise construction costs and delay's monetary value of all EV travellers that need recharging	CPLEX; simulated annealing	Yes
Qin et al. (2022) [99]	Car	Network design (routes)	Minimise energy consumption	Algorithm proposed by the authors (pseudo-code presented)	Yes
Gholami et al. (2022) [201]	Car	Network design (charging facility location), energy network technology	Minimise power loss, voltage deviation, and voltage unbalance factor	Differential evolution (DE) / fuzzy Pareto dominance (FPD)	Yes
Piazza et al. (2021) [106]	Multimodal (bicycle, bus, car, shared mobility)	Energy network sizing (power and capacity)	Maximise annual profit	Gurobi	Yes
Beltran et al. (2009) [149]	Multimodal (bus, car)	Network design (routes), frequencies setting, flows on the multimodal network	Minimise operator's, passengers' and external costs	Heuristic route generation algorithm (HRGA) and genetic algorithm (GA)	Yes
Brozynski and Leibowicz (2018) [128]	Multimodal (bus, car)	Energy network technology	Minimise costs	CPLEX	Yes
Allen and Chien (2021) [111]	Rail	Operational aspects (acceleration, speed)	Minimise net energy consumption	Genetic algorithm	Yes
He et al. (2021) [86]	Rail	Network design (routes)	Minimise train traction energy consumption	Differential evolution algorithm based on mutated dichotomy	Yes
Chen et al. (2022) [96]	Rail	Rail scheduling, operational aspects (acceleration, speed)	Minimise substation energy consumption	Pseudo-spectral method	Yes
Allen and Chien (2023) [112]	Rail	Network design (charging facility location), operational aspects (speed)	Minimise energy consumption and maximise net benefit	Genetic algorithm	Yes

TABLE 7. ***(Continued.)*** **Technology and energy studies.**

Bruglieri et al. (2017) [168]	Shared mobility	Fleet management	Maximise profit	Nearest neighbourhood heuristic	Yes
He et al. (2017) [126]	Shared mobility	Service area	Maximise profit	CPLEX	Yes
He et al. (2020) [183]	Shared mobility	Network design (charging facility location and capacity), fleet management	Maximise annual profit	Algorithm proposed by the authors (pseudo-code presented)	Yes
Wang et al. (2021) [77]	Shared mobility	Fleet management	Maximise daily profit	Genetic algorithm	Yes
Falabretti and Gulotta (2022) [117]	Shared mobility	Charging schedule	Minimise operator's energy costs	Hybridisations of the artificial bee colony algorithm	Yes
Corinaldesi et al. (2022) [162]	Shared mobility	Energy network technology	Minimise energy consumption and costs	Gurobi	No
Lamedica et al. (2022) [107]	Shared mobility	Fleet, charging schedule	Minimise purchasing and electricity charging costs	CPLEX	No

TABLE 8. **Non spatial studies.**

Paper	Transport mode	Decision variables	Objective functions	Solution approach	Model validation
Agaton et al. (2019) [171]	Bus	Technology investment	Maximise the value of the investment	Dynamic optimisation	Yes
Niu and Clark (2021) [161]	Multimodal (bus, car)	Incentive plan for modal shift	Maximise social welfare	Polynomial time approximation algorithm	No
Abdallah et al. (2020) [104]	Multimodal (walking, bicycle, bus, shared mobility, car)	Transportation alternatives for business commuters	Minimise social cost of negative environmental impacts and commuting time	ϵ-constraint method	Yes
Wang and Deng (2019) [69]	Rail	Subsidy plan	Minimise the difference between operation costs and income	Simulated annealing algorithm	Yes
Wang et al. (2020) [75]	Rail	Rail frequencies setting, fares, and subsidy plan	Minimise operational subsidy	Algorithm proposed by the authors (pseudo-code presented)	Yes

investments, subsidies, and fares of public transport systems. In this sense, the main research gaps were identified in the area of urban passenger transport optimisation. The main conclusions point toward including social and human health benefits and quality of life promoted by sustainable transport systems into the optimisation models. Regarding studies of non-spatial measures, it was clear the potential for expanding analyses of fare, subsidies, and public transport financing optimisation as measures of mode shift.

Besides synthesising information on how optimisation techniques are already applied for mitigating climate change through urban and transport planning, topics for future investigation are also provided, as well as directions for enhancements to the optimisation models, allowing researchers to make use of this comprehensive survey to further deepen their studies in the transport sector, essential in the context of climate emergency in which we find ourselves.

As a final remark, it is also important to point out that, although optimisation techniques are methodologies with high computational power, they often lack tools for modelling citizen participation processes, i.e. despite having excellent mathematical and computational performance, the models can fail in basic aspects related to sustainable mobility planning such as democratic participation. It should also be emphasised that the modelling process can be affected by the biases of the researchers themselves. These limitations must be carefully considered when applying optimisation in the area of transport planning, especially when using these techniques to elaborate or give support to sustainable mobility plans.

APPENDIX A PLANNING STUDIES

See Table 4.

APPENDIX B ENVIRONMENTAL VARIABLES STUDIES

See Table 5.

APPENDIX C DEMAND AND TRAFFIC MANAGEMENT STUDIES

See Table 6.

APPENDIX D TECHNOLOGY AND ENERGY STUDIES

See Table 7.

APPENDIX E NON-SPATIAL STUDIES

See Table 8.

ACKNOWLEDGMENT

The authors would like to thank the University of Duisburg-Essen and the Federal University of São Carlos for the facilities provided.

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TATIANE BORCHERS was born in Campo Erê, Brazil, in 1992. She received the B.Sc. degree in civil engineering from the Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brazil, in 2018, with an exchange period at the University of Limerick, Limerick, Ireland (2015 - 2016), and the M.Sc. degree in urban engineering from the Federal University of São Carlos (UFSCar), São Carlos, Brazil, in 2021, where she is currently pursuing the Ph.D. degree. She is also a Visiting Researcher at the Institute of Mobility and Urban Planning (imobis), the University of Duisburg-Essen, Essen, Germany. Her research interests include active and public transportation, optimisation techniques, sustainable and smart mobility, and transport networks planning.

DIRK WITTOWSKY received the Ph.D. degree from the University of Karlsruhe, with a focus on public transport information and user acceptance. He is currently a Professor in mobility and urban planning at the University of Duisburg-Essen and has more than 20 years of experience as a Researcher and a Practitioner. He studied civil engineering in Essen, with a focus on sustainable transport systems. His research interests include the development and design of sustainable transport systems, travel behavior analysis and transport modeling, digitalization, and smart mobility.

RICARDO AUGUSTO SOUZA FERNANDES (Senior Member, IEEE) received the B.Sc. degree in electrical engineering from the Educational Foundation of Barretos, Barretos, in 2006, and the M.Sc. and Ph.D. degrees in electrical engineering from the University of São Paulo, São Carlos, Brazil, in 2009 and 2011, respectively. In 2015 and 2017, he was a Visiting Professor at the Polytechnic Institute of Porto. He is currently an Associate Professor with the Federal University of São Carlos, São Carlos. His research interests include optimization, smart cities, smart mobility, and machine learning.

Open Access funding provided by 'University of Duisburg-Essen' within the CRUI CARE Agreement