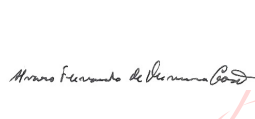


BUS NETWORK DESIGN PROBLEM: A REVIEW OF APPROACHES AND SOLUTIONS

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Ao meu Pai, que me ensinou a perguntar;
À minha Mãe, que me ensinou a responder.

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RESUMO

Os crescentes problemas do congestionamento e da sustentabilidade dos transportes em ambiente urbano causam impactes negativos significativos nas cidades em todo o mundo. As redes de transporte público têm um papel fundamental na mitigação destes problemas, ao permitirem uma mobilidade urbana mais eficiente e com menores impactes na sociedade e no ambiente. As redes de autocarro em particular são essenciais em muitos sistemas de transportes pelo mundo, e o seu planeamento adequado pode ajudar a melhorar a sua eficiência e qualidade, o que, por sua vez, contribui para o objetivo de reduzir o congestionamento e as emissões. O seu processo de planeamento é, no entanto, bastante complexo, e um grande número de investigadores e profissionais têm, nas últimas décadas, dedicado os seus esforços a encontrar melhores soluções. O presente estudo focou-se no ponto de vista da investigação, e o objetivo principal foi o de rever e analisar as abordagens e soluções presentes na literatura existente.

A proposição de efetuar uma revisão de literatura compreensiva deste assunto não é nova, pois outros autores haviam já publicado estudos semelhantes. No entanto, através da comparação das suas estruturas, metodologias de análise e da literatura selecionada por cada um foram encontradas algumas discrepâncias, que por sua vez informaram e motivaram o presente estudo.

Para este efeito, aplicou-se uma metodologia de revisão de literatura semi-sistemática. O método seguido consistiu, em primeiro lugar, da definição da problemática de investigação, que foi seguida pela definição da estratégia para a coleção e classificação da literatura. Os artigos selecionados foram organizados numa matriz de revisão, onde foi resumida e escrita a informação principal relativa aos parâmetros definidos (objetivos, restrições, variáveis de decisão, tipo de aplicação e tipo de problema). Esta informação em texto foi posteriormente categorizada, permitindo um tratamento quantitativo das características principais de cada artigo. Efetuou-se também uma análise descritiva de cada um destes parâmetros.

Esta revisão de literatura resultou numa quantidade considerável de informação relativa à temática em análise, que foi organizada e apresentada de uma forma que poderá informar estudos futuros e responder a várias questões além das que foram inicialmente consideradas. A análise efetuada indicou que uma maioria dos artigos revistos está mais orientada para considerações teóricas do que para aplicações práticas.

PALAVRAS-CHAVE: transporte público, autocarro, desenho de redes de transporte público, desenho de redes de autocarro, revisão de literatura.

ABSTRACT

The growing issues of congestion and sustainability of transportation in cities cause negative consequences for urban communities worldwide. Public transit networks play a key role in the mitigation of these problems, as they allow for more efficient mobility that produces less impacts on society and on the environment. In particular, bus networks form the backbone of many transit systems around the world; good planning of these networks can improve their quality and efficiency, which in turn can help achieve the goals of reducing congestion and emissions. The process of planning these networks is, however, very complex, and many researchers and practitioners have tackled this problem in the last decades. The present work was then focused on the existing literature on the subject from the point of view of research, and the main objective was to review and analyse the approaches and solutions that have been published.

The proposition of a literature review on this subject was not new, as previous authors had already published similar works. However, some discrepancies were identified among them, as their structures, methodologies of analysis, and selected literature were summarised and compared. This work intended to bridge these identified gaps and perform a more comprehensive literature review.

For this goal, a semi-systematic literature review methodology was applied. This methodology consisted firstly of the definition of the research problem, followed by the definition of a strategy for the collection and classification of literature. The selected literature was organised in a review matrix, where the information regarding defined parameters (objectives, constraints, decision variables, application type, and problem type) was summarised and written. The text in this matrix was then categorised, which allowed for a quantitative perspective on the main characteristics of each article. This also enabled a descriptive analysis of the parameters.

This literature review resulted in a large amount of information on the subject, which was organised and presented in a way that may inform future studies and answer further questions on the problem. The analysis performed (specifically on the application cases) indicated however that a majority of the reviewed studies were oriented towards theoretical considerations and not towards practical solutions.

KEYWORDS: public transit, bus, transit network design, bus network design, literature review.

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ABBREVIATIONS AND SYMBOLS

BNDP – Bus Network Design Problem

CNDP - Continuous Network Design Problem

CNDP-T - Continuous Network Design Problem (time-dependent)

DNDP - Discrete Network Design Problem

DNDP-T - Discrete Network Design Problem (time-dependent)

DRP - Driver Rostering Problem

DSP - Driver Scheduling Problem

FS - Frequency Setting

MMNDP - Multi-modal Network Design Problem

MNDP - Mixed Network Design Problem

MNDP-T - Mixed Network Design Problem (time-dependent)

RNDP - Road Network Design Problem

TND - Transit Network Design

TNDFSP – Transit Network Design and Frequencies Setting Problem

TNDP - Transit Network Design Problem

TNDP – Transit Network Design Problem

TNDSP - Transit Network Design and Scheduling Problem

TNFSP - Transit Network Frequencies Setting Problem

TNSP - Transit Network Scheduling Problem

TNT - Transit Network Timetabling

TNTP - Transit Network Timetabling Problem

TRNDP - Transit Route Network Design Problem

UTNDP - Urban Transportation Design Problem

VSP - Vehicle Scheduling Problem

1

INTRODUCTION

1.1. FRAMEWORK

The focus of this study is, as stated in the title, the design and optimisation of transit¹ networks, and specifically bus networks. This contextualisation of the study intends, in the first place, to justify the continued relevance of planning for quality and efficiency of these networks, which are the aims of the studies considered in this review. It also presents the basis for the conceptual framework through which the analysis of the study is developed.

1.1.1. CONTEXTUALISATION

The current issues of urban mobility and congestion have been widely discussed and studied, and still they are very relevant topics that gather interest for research. In the context of the threat of climate change (and the urgent need for more sustainable mobility solutions) and rapid urbanisation (accompanied by the growth of motorisation rates and the social cost of congestion), contributions towards better and more efficient transportation are very pertinent.

In the Global North (or developed countries), although many transit networks have already been well established since the 19th century, car use is still dominant. In the decades following the Second World War, the planning of transportation systems was focused on the provision of infrastructure to accommodate expected automobile demand, which has led to a well-studied vicious cycle of induced demand (Razak, 2013). Although in recent years priorities have shifted, private cars are still the dominant mode of passenger transportation; even though motorisation rates have been stagnating in Europe and North America, the majority of trips are still made by private car (Buehler, Pucher, Gerike, & Götschi, 2017).

This sustained dominance of cars is even more worrying in the Global South (or developing world), where the rapid population growth trend of the last decades is being followed by large-scale urbanisation and economic growth. These trends are creating challenges for cities, as there is a correlation between economic and population growth and motorisation rates. In countries like China or India, this means that a huge number of new cars is entering the roads each year, which is certainly leading these regions into unsustainable situations – both in terms of congestion and emissions (Dargay, Gately, & Sommer, 2007). Although there are already (sometimes informal) transit networks in many large low-income metropolitan areas, they are frequently of poor quality and suffer greatly from congestion and poor

¹ In this study, the term *transit* is used to refer to public transportation for passengers. Although there are many variants, such as *mass transit*, *public transportation*, or *public transport* (each of them having regional connotations), the term *transit* will be used here for the sake of brevity.

infrastructure (Wijaya & Imran, 2019). These considerations highlight the persisting nature of these issues and the relevance of new approaches that are aimed at tackling them.

There are two main alternative approaches to address these issues from the point of view of transit, that however converge on their goal: to shift the focus of mobility from cars and into more sustainable modes. Many planners and engineers focus on the demand side of the equation, developing policies and mechanisms that influence the decisions of travellers towards more sustainable and cost-effective solutions. Others focus mainly on the supply side, through the planning of transit networks that are able to meet the existing demand and provide quality services (Meyer, 2016). The present study focuses exclusively on the latter, with the main object of study being the methodologies and processes that aim to design or improve bus networks.

Busses are, when compared to other modes of transit, cheaper and more flexible, especially when compared to rail-based transit systems (which require much larger investments) (Button, Vega, & Nijkamp, 2010). Thus, they are the main mode of transit in many cities around the world (even in huge metropolises), forming the backbone of mobility for millions around the world (Loh & Xiang, 2014).

There is still, however, the question if the design of quality bus networks can play an important role in the mitigation of these problems. Although this is not the main focus of the present study, there have been previous studies that indicate that this approach may play an important role in this mitigation. Beirão and Sarsfield Cabral (2007) performed a study on comparisons between attitudes towards both cars and buses, and concluded that, even though there is a perception of personal vehicles as being the better mobility option, the improvement of several key parameters of bus transit supply can indeed help shift the modal choices. Although they, as Parkany, Gallagher, and Viveiros (2004), consider that the potential attitudes of passengers towards transit as a whole play an important role in modal choice, the perception of the quality of existing bus transit systems – namely, of qualities like short travel times and reliable service – is a key component of this choice. The results of this study also showed a preference towards frequent and direct service, with a further emphasis on comfort (avoiding crowding and having an available seat).

The question that follows the previous considerations is, naturally, how to actually plan a quality bus network. A definitive answer to this question is certainly larger than the present thesis (and perhaps impossible), but for decades planners have worked towards it in practical applications. Transit networks are ubiquitous worldwide, and decades of practice in designing and improving them have produced ample evidence of both successes and failures; this has often resulted in the publication of practical guidelines and “rules” that are intended to guide this process, establishing measures of good practice in this field. Some examples that were found in a quick survey include the report published by Transport for London (2012), where goals and directives are established regarding stop location, service frequency, reliability, and cost, or the report by Florida Department of Transportation Research Center (2009) where similar measures of quality networks are derived from observation. Ceder (2007) argues that these guidelines and service standards are widely used by transit agencies in the planning process, stating that more than half of the agencies in the United States and Europe applied them. The author also argues that these fixed guidelines are mostly outdated, and that there is much room for improvement both in the guidelines themselves and for innovative approaches to the process.

Another approach to solve the question of how to effectively plan a bus network has been studied from the perspective of operations research. As previously stated, this subject has gathered much attention from research since the 1960s, as a large amount of literature has been published that is aimed at solving it as a mathematical optimisation problem. This approach is aimed at designing an optimal system that maximises or minimises a number of pre-established objectives. However, from a computational point

of view, this is a very complex problem, with some authors even classifying individual sub-problems of the overall process as NP-Hard (Guihaire & Hao, 2008). Thus, a wide variety of solutions have been proposed, with varying degrees of simplification of the “moving parts” of the problem and with according methodological sophistication. These solutions have also been accompanied by an evolution of information technology that has further enabled their application, as computer processing power has become widely available and cheap. At the same time, the technology on the vehicles themselves has evolved, as the collection of data on the network becomes easier and the data itself is richer and more detailed. This has opened opportunities for the development of computer aids for the planning process, as well as the automation of several tasks that may be done through algorithms; it has also enabled the development of more complex and sophisticated methods in research, which may be more computational power-heavy.

The current study focuses on this approach, as its title indicates; the main focus is to appraise the existing approaches from research that apply an optimization perspective to the problem of designing and improving bus networks. But another question that has motivated this study is whether there is a gap between these two approaches. The hypothesis is that there is a disconnection between the solutions that are proposed by researchers and the actual needs of planners, as many studies appear to be oriented towards theoretical advances in computation instead of better solutions that can be applied in practice. The present study does not intend to answer this question fully, as it only focuses on one side of the equation, but it may help to shed some light on the shortcomings of past and current academic efforts to provide solutions to the problem of designing good bus networks.

Another important distinction lies between two of the main entities that shape the problem: the **user** and the **operator**. The definition of the objectives for the optimisation is necessary for the development of models and methods, and there is a consensus that the BNDP is inherently multi-objective because of this distinction. The **users** can be defined as the passengers of the network and are the reason the network exists in the first place – they create the demand for travel. As previously discussed in this chapter, users generally desire fast, frequent, and comfortable service that goes where they want to go, and the objective of satisfying the user’s needs is important to achieve quality networks.

Bus networks exist in many forms and organisational paradigms, with varying degrees of involvement of both public and private entities in its planning and operation. Thus, the definition of **operator** might not be straightforward, as the amount of regulation and privatisation that exist in different locations influences the scope of its role. Nonetheless, it makes economic sense to consider that these entities converge on the common objective of minimising costs for running the network, whether from a perspective of reduction in public spending or, in the case of private companies, profit maximisation. These objectives are important for the viability of the network and its sustainability and are reflected in a rational distribution of resources and adequate service for the existing demand.

At a first glance, it may seem that these objectives are contradictory, as a user-focused increase of the quality of service can be incompatible with the reduction of operator costs. This apparent trade-off is very relevant in the definition of optimisation models, and different authors appear to have different approaches to how they achieve balance between both sides; some focus more on increasing network quality while others are more directed at cost reduction and network rationalisation. It is then a relevant objective for this work to understand what objectives are dominant and how the authors balance them.

1.1.2. CONCEPTUAL FRAMEWORK

This thesis intends to contribute towards the understanding and systematization of previous approaches, and for that goal it is helpful to provide a short overview of the problem's framework as defined by previous authors. Previously published literature reviews have also discussed this framework, as will be detailed further in Chapter 2, but it is relevant to present the main concepts that define the problem in broader strokes as a basis for further analysis.

One of the earliest formal structures proposed for the Bus Network Design Problem (BNDP) was published by Ceder and Wilson (1986). This was a landmark paper, as the structure proposed by the authors (presented in Figure 1, which is directly adapted from the original) has been widely cited throughout the years. The planning process is divided into five planning activities: **network design, frequency setting, timetable development, bus scheduling, and driver scheduling**. For each of these levels, the authors identify the inputs and outputs that they require, noting that the result of each step is a necessary input for the next step but it is also retroactively relevant, i.e., the results of further steps can influence previous ones. This amounts to an almost iterative process, where in order to obtain near-optimal results these steps should be repeated including the previous results. The authors also argue that this is a cumbersome process to perform manually (especially the last two steps), which shows the advantages of automated computer applications to aid the planning process.

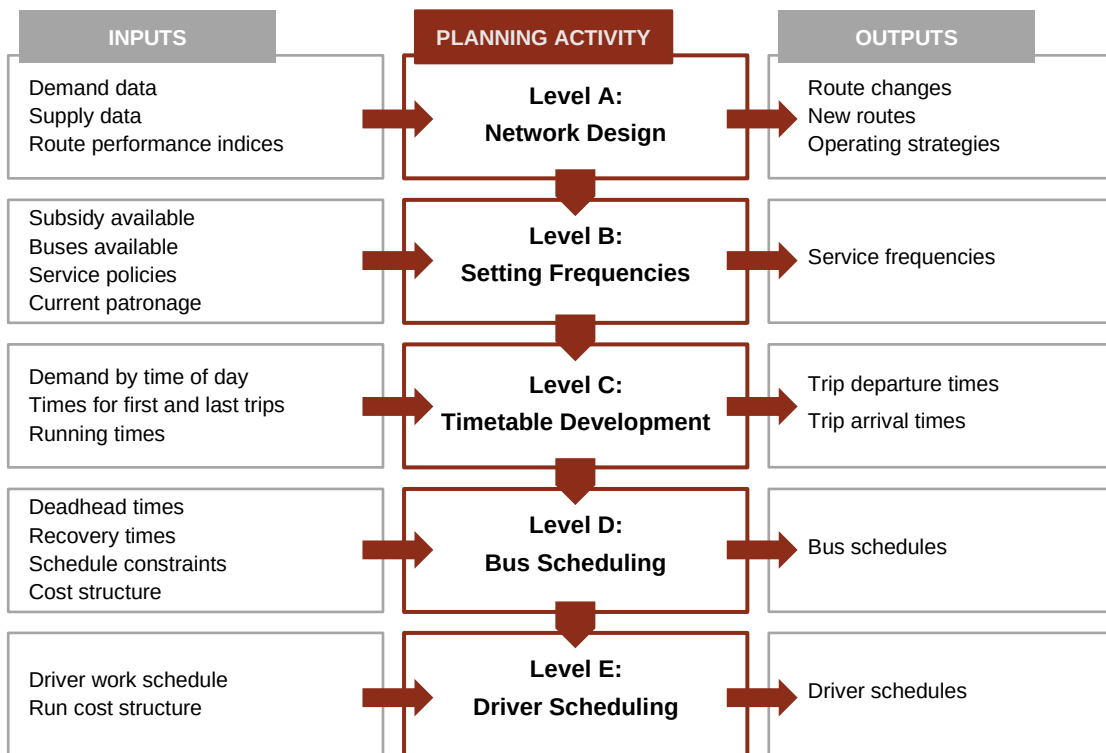


Figure 1 – Bus network planning process. Adapted from Ceder and Wilson (1986)

The first level – **network design** – concerns the definition of the network topology, including the design (or adjustment) of routes and stops, as well as the determination of the location of terminals and interchanges. It can mean the definition of new lines in the establishment of a new network or in the expansion of an existing one, or the adjustment/alignment of already established ones. The second level is **frequency setting**, which defines the adequate level of service for each line in the existing or planned network, while considering the available resources and existing policies. The **timetable development** level follows the previous one closely, as it converts the designed frequencies into fixed arrival and departure times for each stop. Both of these levels consider the existing demand, which is varied in time; different times of day require different service patterns (such as on and off-peak times), and timetables take into account seasonal variations in demand. The last two levels, **bus** and **driver scheduling**, allocate the required resources to the network; the vehicle scheduling activity consists of creating chains of trips for each vehicle in order to achieve efficient operation, while crew scheduling consists of the assignment of drivers to vehicle trips, considering constraints such as contracts and working hours. (Ceder, 2007)

Ibarra-Rojas, Delgado, Giesen, and Muñoz (2015) have also complemented this structure by grouping these five steps through their scope and their planning horizon. They considered that the first level (network design) concerned decisions on a **strategic** dimension, as changes in network topology are planned in the long-term. The decisions in the frequency setting and timetabling levels were considered to belong on a **tactical** dimension, as the cost of changes at these levels is lower than at the network level and the timeframe for these decisions is shorter. The lower levels of vehicle and driver scheduling were considered to belong to the **operational** dimension, as they align daily operations of the network to the strategic and tactical goals previously defined.

The definition of the main problem studied in the present work is based upon the structure presented in Figure 1. The Bus Network Design Problem (BNDP) is here defined as the combination of decisions made at strategic, tactical, and operational levels that result in the definition of a bus network, from its topology to its operational configuration.

1.2. OBJECTIVES

The main objective of this study is to construct a comprehensive review of the research that has been conducted on solutions for the bus network design problem, in order to produce insights on the key variables and parameters and on the structure of the problem through the point of view of the existing body of research. It is oriented towards the organisation of existing approaches through a systematic collection and classification of literature, so that it may enable further understanding of the problem and serve as a basis for better solutions.

The literature review not only intends to organise and present the existing body of research but also to analyse it. The objective is, in this case, to find connections between the defined parameters of analysis in order to identify recurring trends, so that a more robust categorisation of approaches can be made. Although the goal is to perform a broad analysis of the subject, some of the previous considerations in this chapter also warrant interesting hypotheses that may be formulated as research questions, such as:

- Do existing studies focus on the perspective of the user, the operator, or both?
- Is there a gap between research and practice?

These questions are two that have been chosen from many possible ones, as there may be many other relevant paths of research on this topic. Thus, the intention of these questions is to guide the study, as the analysis itself may produce other interesting directions, possibly being able to go as far as to identify possible gaps that may be addressed by future studies.

1.3. STRUCTURE

The present study is divided into five chapters, and a brief summary of each is presented in this section.

Chapter 1 is an introduction to the present work, summarizing its structure and the objectives that were established. It provides a framework that serves as an introduction to this work, defining the main issues that are addressed.

Chapter 2 analyses the existing treatment of the subject in literature, with particular focus on existing comprehensive literature reviews. The analysis and comparison of these works serves as a motivation and basis for the main body of this study that will be discussed in the following chapters.

Chapter 3 defines the methodology applied to construct the literature review, setting the criteria for inclusion or exclusion of specific works. The procedures that were taken to categorize and define the analytical variables are described, and their final definitions are presented and organized into categories, structuring the analysis in the following chapter.

Chapter 4 presents the results of the review on the selected works through the methodology defined in the previous chapter, grouping them into the previously defined categories. The attributes found in each work are compared and analysed.

Chapter 5 summarizes the conclusions and main findings of this work and indicates possible research gaps that may exist.

2

ANALYSIS OF EXISTING LITERATURE

2.1. PREVIOUS LITERATURE REVIEWS

As stated in the previous chapter, this study intends to review the existing approaches from research to solve the Bus Network Design Problem. However, this attempt at reviewing the problem is not new. This field of research, for its relevance and complexity, has attracted much attention throughout the years and a large amount of studies have been published. This has naturally motivated several authors to perform state of the art reviews as a basis for their own studies, as the study of previous approaches is very relevant and informative in this particular subject.

The paper by Ceder and Wilson (1986) that was previously discussed is still widely cited, as the model they proposed is still applied by authors in more recent times to either measure their own positioning on the problem or classify existing literature in the case of systematic reviews (as will be discussed further); they established a model of the bus line planning process as a five-step sequence of decisions. In this work, they also surveyed previous approaches to the problem in terms of parameters and solution methods, which was not very extensive due to the small number of studies published at the time.

The article published by van Nes, Hamerslag, and Immers (1988) also included a survey of existing optimization models, where they established a classification of six different model categories and exemplified each one with relevant studies. Later, L. Spasovic, Boile, and Bladikas (1994) presented their state of the art review in the form of a matrix, where they also identified the decision variables, objective function, transit mode, demand model, and network geometry adopted in each paper. This review was also very sectorial, as they only reviewed analytical solutions to the problem that were pertinent for their own approach. More recently, W. Fan and Machemehl (2004) presented an extensive review of the subject also as a support to their study, where each paper was individually summarized. Other authors such as Agrawal and Mathew (2004), Cevallos and Zhao (2006), and Cancela, Mauttone, and Urquhart (2015) have also presented their own short reviews on existing solutions that were relevant to their own analysis and solution proposals.

None of these were, however, attempts at global reviews of the problem. They were limited in scope to their own contributions to the literature, as they were performed as a way to support their own research and not as an end in itself. Chua (1984) tackled the bus line planning problem in a global way but not entirely through literature review; the main concern of the study was a survey on techniques applied in practice by British bus operators and planners in the 1980's. Schöbel (2012) published a narrative review on models and methods for line planning; it focused only on this aspect of the larger problem of network planning, without considering the interaction with frequency setting and timetabling. The author identified basic solution approaches and general formulations present in the literature, presenting a theoretical

overview of the problem. However, this review did not present a structured approach or a review matrix to systematize its conclusions, and as such was not considered to be an attempt at a global review.

Nonetheless, there have been attempts at building true systematic reviews of the transit network design problem. As of this study's conclusion date, four such reviews have been found: the studies published by Guihaire and Hao (2008), Kepaptsoglou and Karlaftis (2009), Farahani, Miandoabchi, Szeto, and Rashidi (2013), and Ibarra-Rojas et al. (2015). Each of these four papers proposes a global literature review of the problem, albeit with different focuses and methodologies, and they are the most interesting to inform the current attempt at such a review. Their analysis is key to not only understand the problem and the different ways it has been modelled and organized but also to guide the review process of the present work. Each of them will be studied in detail in the following section, identifying their motivations, methods, organization, and conclusions.

2.1.1. GUIHAIRE & HAO (2008)

The earliest of the four systematic reviews of the problem was published by Valérie Guihaire and Jin-Kao Hao in 2008. The authors present three main motivations to conduct the study; the first is that, acknowledging that previous studies presented interesting overviews of specific parts of the problem (mostly as a state of the art review to consolidate their own studies), there was a lack of systematic reviews that allowed a global view of the subject. The second motivation was related to the evolution of public transit policies, more particularly around the concepts of intermodality, integration, and deregulation, that affected the solutions applied to transit planning. Lastly, they mentioned the recent evolution of solution methods and the need for a global review that emphasized their gains in efficiency and applicability.

The authors start their analysis from structure proposed by Ceder and Wilson (1986), which divides the problem into the five steps that have been discussed in the previous chapter. They acknowledge that, ideally, these steps should be treated simultaneously in order to obtain optimal solutions; they are very interconnected, as a solution for one of them impacts the optimality of the other steps. However, they also consider that solving the five steps simultaneously appears to be intractable due to the overall complexity, which has led most solutions throughout the years to be sequential in nature, i.e., solving each step individually.

The review was constructed according to an explicit methodology, where the authors first defined the search strategies for the selected literature; they performed a search on international review databases complemented with a free web search and an ancestry approach. The search was guided through the definition of keywords that restricted the results to the subject; to bridge linguistic gaps, these keywords also included alternative denominations for similar concepts.

The authors structured the problem in a sequential way, according to the first three steps of the process. For this structure, they proposed a terminology to define each type of problem reviewed, which consisted of a subdivision of the first three steps of design, frequency setting, and timetabling. On a first level, they separated these steps in individual sub-problems, for the categorization of studies that only solved one of them. For more complex approaches, the authors considered combinations of these steps, namely design and frequency setting and scheduling (frequency setting and timetabling), as is shown in Figure 2. Finally, they classified studies where the three steps were combined in one analysis, which they classified as design and scheduling problems.

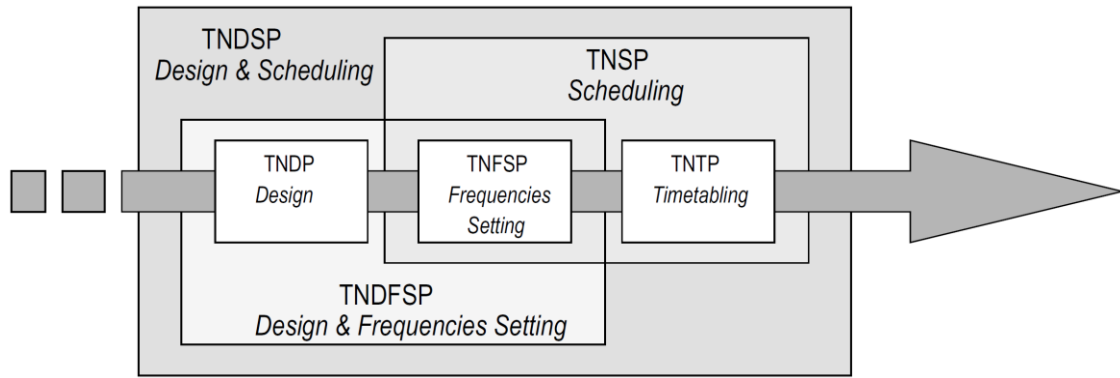


Figure 2 - Proposed structure of the TNDSP. Source: Guihaire and Hao (2008)

The review itself was divided by these combinations of sub-problems, with the authors considering the isolated problems first (TNDP, TNFSP, and TNTP) and then the composite problems (TNDFSP, TNSP, and finally TNDSP); each of these categories was further divided by methodological approach (mathematical, heuristic, neighbourhood search, and evolutionary algorithms, along with some other different approaches), and the papers were reviewed one by one in text. They also summarized their findings in a review matrix where they identified the problem category and the methodology for each article, along with the objectives, constraints, and application case.

The conclusions presented by this paper start with the connection between the findings of the review and the real context in which planners perform their activities. They consider the weight that optimized network design, frequency setting, and timetabling have on the efficiency and competitiveness of transit operators and the importance of the optimization objectives that are set, specifically in the context of the debate between competition and cooperation between operators that the authors consider to be growing. They also identify gaps in the existing research and opportunities for future work; they argue that there is a need for more attention to more specific sub-problems (such as intermodality, synchronization management and intercity transit), as well as taking advantage of technological progress and integrating more practical concerns into the optimization models (such as adaptability, stochasticity, and demand responsiveness).

2.1.2. KEPAPTSOGLOU & KARLAFTIS (2009)

Kepaptsoglou and Karlaftis performed a review in 2009 where they collected 62 papers on the subject (Transit Route Network Design Problem, as stated in the study's title). They present a structured review on the problem, focused on its framework and the interaction of all its identified parts.

Their methodology for the literature review is not explicitly defined, in contrast to other authors that present inclusion criteria and search strategies. Thus, the selected body of literature for the review, while extensive, is not directly justifiable and may contain bias. The problem definition is not directly stated, but it may be inferred from the structure proposed by the authors; they cite the five-step structure proposed by Ceder and Wilson (1986) but focus mainly on network design and frequency setting, as decision variables related to the other three steps are not present in the review matrix.

It is interesting to note that this study does not cite the previously mentioned review published by Guihaire and Hao (2008), which can possibly be explained by both being almost contemporaneous. They roughly cover the same subject; although this study does not have such an explicit thematic definition as the previous one, the chosen literature solves the same first three steps of the problem (network design, frequency setting, and timetable development). A more detailed comparison of these studies will be presented further.

Instead of focusing on the aforementioned steps as Guihaire and Hao (2008), Kepaptsoglou and Karlaftis developed a structure to contextualize the multiple parts involved in transit network design, and organized the paper around those definitions. They started with the definition of the objectives for the design and whether they were single or multiple, and the influence they had on the parameters and methodology applied. Then, they analysed the different parameters involved in the design problem, such as the decision variables, the network structure, the demand patterns and characteristics, the constraints, and the optimal operational strategies, mentioning examples from the selected body of literature for each concept. Finally, the authors focused on methodologies, analysing the approaches (conventional, heuristic, or other) that were taken in research to solve this complex problem. Each of these three layers is divided into its own subcategories, where the authors present a short summary of relevant papers that exemplify them.

The authors also present a review matrix for all the 62 studies considered, that is organized in the three-fold structure previously described (objectives, parameters, and methodology). Within the “parameters” category, only the decision variables, the demand patterns and characteristics, and the network structure are listed for each paper; the constraints and operational strategies, while included in the proposed structure and defined in the main body of the review, are not included in the matrix. There is also a second matrix for a more detailed classification of heuristic and metaheuristic methodological approaches, where only 28 of the 62 papers are analysed.

The main conclusions that the authors propose are related to the definition of a structure to the network design problem. This structure, that is presented in Figure 3, is an illustration of the framework that the authors propose for the process. They consider a hierarchical order of importance for the three main layers, starting with the definition of objectives, which they argue that is motivated by the goals and policies of the operator and the environment of the application. The definition of objectives also must deal with the inherently multi-objective nature of the problem, as the interests of its two main stakeholders (users and operators) must be balanced. The authors consider that the “parameters” layer comes next, which includes the definition of the main “working parts” of the problem – its decision variables, constraints, demand patterns (dependent on use and urban form), and operational strategies (which reflect the policy and resources of the operator). They also consider these two layers as the “design space” of the problem, in opposition to the “methodological” layer which handles the modelling characteristics of the problem. The authors argue that this aspect is the one that has had more attention from research, and the review presented a variety of methods that can suit different levels of detail of the design environment (as required by the problem definition) and different levels of computational power available.

As a conclusion, the authors identified some shortcomings of the existing research that could be improved by future works, considering that, even though an extensive number of articles has been published on the problem, there is still a large potential for more studies. They commented on the need for improvement of the solutions, especially on the realism and practical usefulness of the methodologies. They also suggested further research on different demand scenarios (other than daily use, such as disruptions or mega-events) and on more complex models that could incorporate more design objectives.

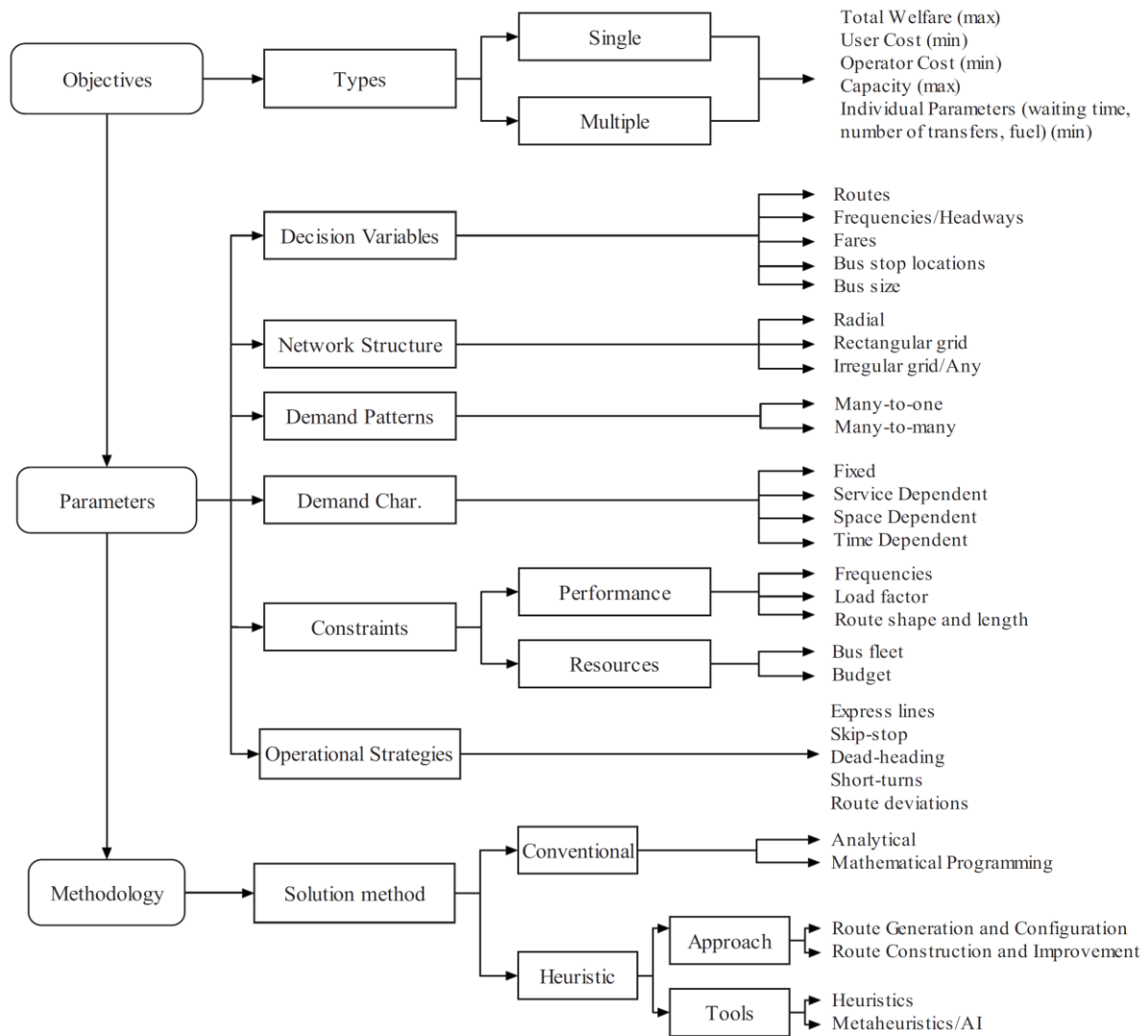


Figure 3 - Proposed hierarchy of the TRNDP. Source: Kepaptsoglou and Karlaftis (2009)

2.1.1.3. FARAHANI ET AL. (2013)

Farahani et al. (2013) propose a much wider view of the problem in their review paper, defining it as urban transportation design problem (UTNDP). This definition encompasses a holistic view on transportation issues in urban settings, combining road network design (RNDP) and transit network design (TNDP), as well as the interaction between the two in multi-modal network design (MMNDP). The problem definition includes both private and public transportation in optimization studies, as the authors focus on both the solution to existing mobility problems and the planning of new transportation infrastructure.

The authors justify this holistic approach through the argument that RNDP, TNDP and MMNDP share the same subject (urban mobility) and are part of a larger problem (UTNDP), and argue that the lack of reviews that directly compare solutions for these problems hinders the cross-fertilization between different fields of study. They also define the scope of the review to be only related to decisions that define the topology of the network, either on the strategic or tactical level, not considering operational approaches or tactical decisions that do not affect the shape of the network.

The review itself is split in three ways, as the authors have analysed each problem through a different lens. They present six different review matrices; in the first three they organize the selected literature according to various criteria that depend on the problem, and they subsequently present three tables summarizing only the cases with real application. Unlike the previous reviews, this one does not present individual summaries for the selected articles; instead, it presents these individual considerations in the review matrix only and constructs a more generalised analysis in the body of the article.

The first matrix summarizes the review on RNDP, separating it in discrete network design problems (DNDP – deals with discrete decisions such as adding new roads or lanes or changing traffic direction), continuous network design problems (CNDP – deals with continuous decisions such as capacity expansion or toll-setting), mixed network design problems (MNDP – a combination of the two previous approaches), and time-dependent network design problems (a subset of the previous problems where the conditions change over the planning horizon – DNDP-T, CNDP-T, MNDP-T). The categories considered in the analysis for each study are the objectives (and whether they are single or multiple), the traffic assignment model, the demand model (fixed or elastic), the type of decision taken, and the solution method; the objectives and decisions are presented in a different table, where they are grouped into labels and a dot (Boolean-type value) is attributed to each one, making it easier to read and compare information (figure 4). This organization of the review matrix served as an inspiration for the presentation of the results in the present study, as will be discussed in Chapter 3.

Reference	Objective						Single/ multiple optimization	Traffic assignment	Demand	Decision			Solution method
	Max. consumer surplus	Max. reserve capacity	Min. total vehicle miles	Min. travel + construction cost	Min. construction cost	Min. total travel time/ cost				Determining road tolls	Scheduling traffic light	Street capacity expansion	
Steenbrink (1974a)			•				S	SO	F			•	Iterative-Optimization-Assignment Algorithm
Abdulaal and LeBlanc (1979)			•				S	DUE	F			•	Powell's Method, Hooke and Jeeves Method
Dantzig et al. (1979)			•				S	SO	F			•	Iterative Decomposition, Lagrangian Multiplier
Marcotte (1983)			•			•	S	DUE	F		•	•	Exact Algorithm Based on Constraint Accumulation, Heuristic
LeBlanc and Boyce (1986)			•				S	DUE	F		•	•	Bard's Algorithm

Figure 4 - Excerpt from the RNDP review matrix. Source: Farahani et al. (2013)

The second matrix, pertaining to the TNDP, is perhaps the simplest, where only the constraints, objectives, and solution methods are identified and categorized. The authors separate the table into pure TNDP problems, where only the topology of the network is addressed, and TNDPSP, where the service frequency is also optimized; in comparison with the other two previous reviews considered, the focus is also on these two first steps of the model cited by previous authors, but the analysis is much more simplified, as the overall scope of the study is much wider. The multimodal problem (MMNDP) is reviewed in another separate matrix, where the authors consider the type of decisions, the lower-level problem that is solved, the modes considered, whether there is flow interaction between modes, the approach, the objectives, and the solution method.

Additionally, the authors present a summary of existing case studies in the selected literature, dividing the analysis into three separate matrices (one for each considered sub-problem) that are similar to the previous review matrices. They conclude that most studies do not include case studies, especially those that deal with road network design problems, through which they question the practicality of some of these approaches. The sample size of the data used for each case study is also presented in the matrix, enabling a comparison of the efficiency of the models for larger (more realistic) databases.

This three-fold structure of the sub-problems is also present in the conclusions, where the authors summarize their outlooks and future research directions separately. As the present study deals only with the TNDP, the authors' conclusions for the other problems will not be considered in this section; it is

however interesting to note that they are much more extensive, as for this particular problem only three existing research gaps were identified. They propose that future studies on TNDP should incorporate environmental concerns into the defined objectives, as well as time-dependent approaches that involve strategic decisions. They also consider that more advanced passenger behaviour simulation could be included in the lower-level problems, as current approaches apply simplified passenger choice models.

2.1.4. IBARRA-ROJAS ET AL. (2015)

The review by Ibarra-Rojas et al. (2015) is the most recent of the four reviews considered in this study. Its difference towards the other three is immediately visible in its title, where the authors propose not only to review the problems surrounding the planning of transport systems but also their operational configuration and real-time control. The stated objective is to develop a comprehensive classification of the existing body of literature, complementing and expanding upon the already existing literature reviews.

The authors propose a structure that is, like the other authors before them, based on Ceder and Wilson (1986), although they consider six sub-problems: transit network design (TND), frequency setting (FS), transit network timetabling (TNT), vehicle scheduling problem (VSP), driver scheduling problem (DSP), and driver rostering problem (DRP). They consider these sub-problems as inherently interdependent, as they show on Figure 5; although the authors' model includes some form of hierarchy, it is not entirely sequential, as their proposed framework considers the existence of both upstream and downstream influence of the various levels. This model is different from previous authors, as they organize its parameters according to inputs, sub-problems, and outputs. The inputs correspond to various types of constraints of the model that are relevant at different stages of the planning process (network topology and characteristics, service level standards, driver work constraints, etc.), while the outputs correspond loosely to the main decision variables of each problem level (configuration of lines and stops, frequencies, fleet size, schedules, etc.).

This review is, in comparison to the previous ones, apparently the only one to exclusively consider bus systems and not transit as a whole, excluding from the analysis articles that study rail systems or multi-modal problems (although they consider some rail-based studies with the justification that they also apply to bus problems). It is also the only one to explicitly consider vehicle and driver scheduling and rostering as an integral part of the review, as previous authors have only focused on the first three steps of the BNDP. They also went even further to also consider a "control" level that corresponds to decisions made in real-time in the network, in a way that is even more granular and detailed than operational optimization. Thus, their review was focused on four simultaneous levels of decision: strategic, tactical, operational, and real-time control.

In comparison to Guihaire and Hao (2008) and Kepaptsoglou and Karlaftis (2009), this review presents a more complete view of the problem, as they limited their analysis to the first three steps of the problem (network design, frequency setting and timetabling). With respect to Farahani et al. (2013), this study is also quite wide in its scope, but presents a more vertical view of the problem while the previous one views it more horizontally.

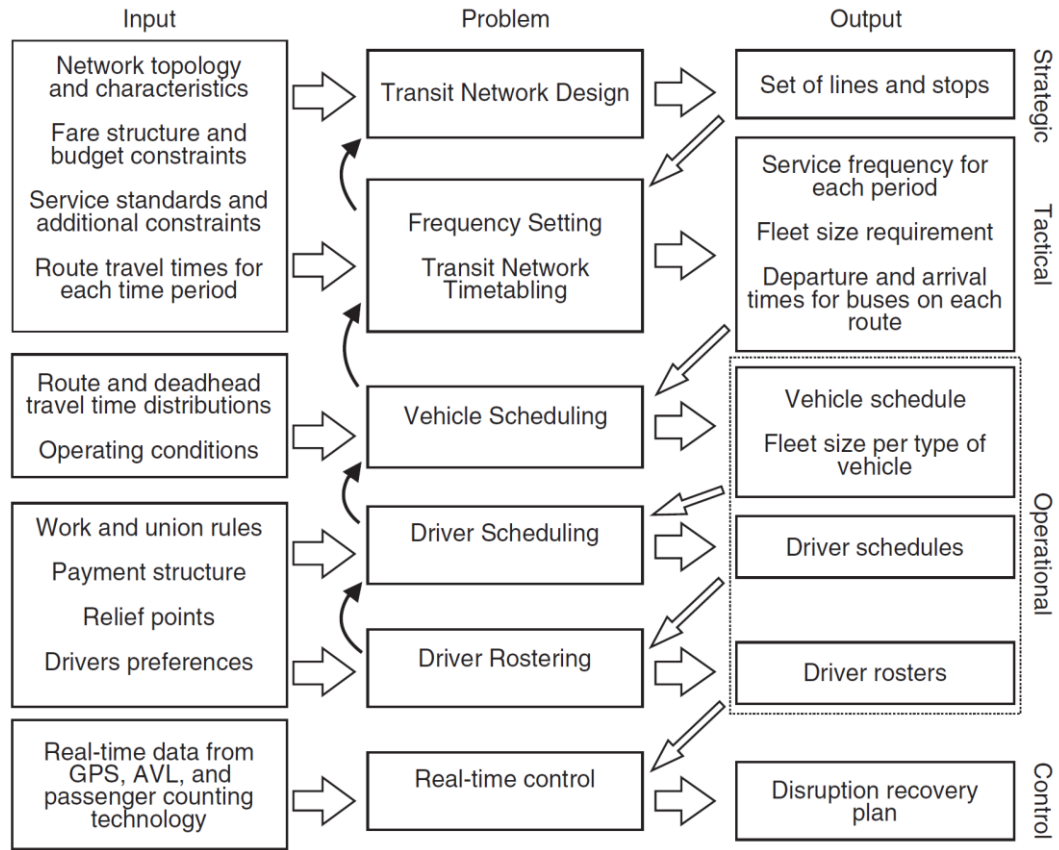


Figure 5 - Proposed model for TNP. Source: Ibarra-Rojas et al. (2015)

The review itself is divided through the decision levels, with the authors dividing the problems that consider strategic, tactical, operational, and real-time decisions. For each of these categories, they present a review matrix and a brief summary of the main characteristics of each article reviewed; like Guihaire and Hao (2008), they also divide each category by methodological approach, but in this case the authors not only consider solution methods but also different modelling approaches. Adding to these categories, the authors present a further section where they analyse the existing combinations between sub-problems. They consider articles that integrate different steps of the network planning process (specifically, among timetabling and vehicle scheduling, vehicle scheduling and driver scheduling, and driver scheduling and rostering), reviewing the methodologies applied for solving these sub-problems simultaneously.

The conclusions of this literature review consider that, although there has been a large number of publications on this subject, there are still more possibilities for further development. The authors identified three possible future directions for research: the development of more dynamic approaches to the vehicle and driver scheduling problem that take uncertainty into account, the consideration of different combinations of limited-stop lines and transfer coordination, and, lastly, the further integration of sub-problems that are currently solved separately.

2.2. CRITICAL ANALYSIS

As previously discussed in this chapter, each of the previous reviews on this subject has contemplated it differently and contributed in its own way to the organization of the field. The nomenclature and structuring proposed by each group of authors have been individually addressed, as well as the criteria and the methodologies applied for their reviews.

In an initial phase of this study, these review articles were key to understand the problem and its specificities; however, after an initial analysis, their shortcomings became evident, and they served themselves as a motivation to perform the present study. The different approaches that have been individually addressed in this chapter add some confusion to an already complex subject, as both the structure of the problem and the methodologies are not unanimous, and the criteria applied for each review is not clear. Therefore, a critical analysis of previous reviews is helpful to identify these shortcomings and to construct a more informed review, which is the subject of the present work. However, the different ways of classifying the problem and organizing the literature also create problems for the direct comparison and analysis of the review papers themselves; thus, this critical analysis will be divided in two axes: first, a comparison of the scope assumed by each author and the methodological construction of each review, and then an analysis of the disparity between the selected literature in each review.

2.2.1. SCOPE AND STRUCTURE COMPARISON

The network design problem, as a whole, is very complex; as previously discussed, this complexity arises not only from the large number of variables involved and the difficulty to obtain optimal solutions but also from its multidisciplinary nature and the multitude of different approaches that have been taken in research. Thus, any global review that may be performed on this subject should require the construction (or, at least, selection) of a model through which the problem is analysed. This models usually include the definition of nomenclature (in order to clarify the classification of different variables and sub-problems) and a “tree” of sub-problems that are associated with the main issue, with or without hierarchy and order.

This construction or selection of a model for the problem creates an additional challenge for the author, as it requires a balance between simplification and detail. It is clear that, for a problem with such complexity, some degree of simplification is necessary for a useful categorization of the existing research; however, too much simplification can hide the finer nuance that is also important for the understanding of the problem. Also, the definition of the scope of the study is also very important in this sense, as a view of the problem that is too wide (that includes a large range of similar sub-problems) may lead to a shallower analysis, while narrowing it too much may lead to an overly sectorial study, losing sight of the bigger picture. It is thus important to analyse how each review positioned itself on this scale and if the authors achieved a balance between scope and complexity.

Guihaire & Hao (2008)	Transit Network Design and Scheduling Problem (TNDSP)	• Network Design (TNDP) • Frequency Setting (TNFSP) • Timetabling (TNTP) • Scheduling (TNSP) • Design & Frequency Setting (TNDFSP)
Kepaptsoglou & Karlaftis (2009)	Transit Route Network Design Problem (TRNDP)	• Route design • Frequency Setting
Farahani et al. (2013)	Road Network Design Problem (RNDP)	• Continuous Network Design Problem (CNDP) • Discrete Network Design Problem (DNDP) • Mixed Network Design Problem (MNDP)
	Transit Network Design Problem (TNDP)	• Network design • Frequency setting
	Multimodal Network Design Problem (MMNDP)	
Ibarra-Rojas et al. (2015)	Transit Network Planning Problem (TNP)	• Transit Network Design (TND) • Frequency Setting (FS) • Transit Network Timetabling (TNT) • Vehicle Scheduling Problem (VSP) • Driver Scheduling Problem (DSP) • Driver Rostering Problem (DRP)

Figure 6 - Comparison of models adopted by each author

Figure 6 shows a summary the scope of each review in terms of the model they adopt for the classification of sub-problems, including the nomenclature that each has used for them. It summarizes the previous considerations about each review and demonstrates the differences and similarities that exist between them. It is immediately visible that Farahani et al. (2013) has the widest scope of all four, as he not only reviewed problems related to transit (and, specifically, buses) but also road and multimodal network design; as previously stated, this review is wider but shallower in scope than the others, as the attention given to the TNDP individually is smaller. On the other hand, Kepaptsoglou and Karlaftis (2009) do not show much thought on a specific model for the problem, as the structure of their paper is focused on the functional steps for solving the problem (objectives, parameters and methodologies); nonetheless, the results for their review show that they limited their analysis to the strategic aspect of network planning (network design and frequency setting), making their scope even narrower than other authors. Ibarra-Rojas et al. (2015) perform a different study, narrowing their focus to bus network design only and simultaneously going deeper into the operational aspect of network planning (and even into real-time control strategies), being the only study that includes vehicle and driver scheduling and rostering as an integral part of the analysis.

Another difference in the structures of all four reviews is the parameters chosen for the analysis of the literature. All authors presented some form of review matrix as a way to organize and present the results of their literature review, but the organization of these matrices diverged. Specifically, the differences

were on the parameters identified in each column, as some authors chose different aspects to focus on. As it is possible to see in Table 1, the only common elements of classification were the objectives and the solution methods, as all authors listed them for each paper analysed. However, other aspects were different among the reviews, as, for example, only Guihaire and Hao (2008) chose to identify the problem definition according to the structure they proposed for the problem (as shown in Figure 2). Kepaptsoglou and Karlaftis (2009) chose to list the decision variables of each problem while the other three reviews listed the constraints; none of the reviews listed the two simultaneously. This review also gathered information from each paper on other parameters, such as the network structure considered in the model (rectangular, radial, etc.), the demand pattern (many to one, many to many), and the demand characteristics (fixed, elastic, etc.). Additionally, all other three authors reviewed the existence of application cases in each study, with Guihaire and Hao (2008) and Ibarra-Rojas et al. (2015) also considering the type of application that was employed (example, real case, benchmark, etc.).

Table 1 – Parameters analysed by the previous authors in their review matrices

	Problem Definition	Objectives	Constraints	Decision Variables	Solution Method	Case appl.	Other (network, demand, etc)
Guihaire & Hao (2008)	●	●	●		●	●	
Kepaptsoglou & Karlaftis (2009)		●		●	●		●
Farahani et al. (2013)		●	●		●	●	
Ibarra-Rojas et al. (2015)		●	●		●	●	

2.2.2. METHODOLOGY COMPARISON

According to Toronto and Remington (2020), for a systematic review to be considered rigorous, it must have a comprehensive method that is followed and reported. This is necessary for the evaluation of the review itself, as it allows for the reader to identify bias in the selection of literature and synthesis and, if needed, reproduce the study and verify its conclusions. It makes sense that a systematic review mirrors the rigorous methodology of the studies that it considers, and thus it is important that the methodology followed is explicit in the publication.

However, of the four main reviews considered in the present study, only Ibarra-Rojas et al. (2015) and Guihaire and Hao (2008) explicitly define the goals and scope of their reviews, and only the latter presents the methodology and search strategy employed to construct their database. This is a serious shortcoming of the existing reviews, as the lack of explanation of how they obtained their results and structured their analysis undermines the credibility of their results. This is compounded by the lack of consensus on most of the selected literature (that will be discussed in the following section), even on overlapping sub-problems; it is difficult to find explanations for the dispersion of the databases if the authors don't reveal the inclusion and exclusion criteria and the search strategy employed to obtain them. Even more, it is not possible to identify the existence of bias on the selected literature or to reproduce the search to try and obtain the same results, which creates difficulties for both the evaluation of the existing reviews and for them to serve as a basis for further research. These considerations also demonstrate the need for more consistent literature reviews to be published on this subject.

2.2.3. DATABASE COMPARISON

Another important step in the critical analysis of the existing reviews was to build a complete list of all the articles reviewed by each of the authors. This not only created an initial database of articles to perform the literature review (as discussed further in Chapter 3) but also allowed the comparison of which authors cited which paper. This was necessary to demonstrate the disparity that existed between databases, as the different reviews diverged on the selected literature. Some of the reasons that may explain this have already been discussed, such as the differences in methodology and scope, but this disparity was also found in papers that sit within the thematic overlap between the reviews. The method applied to perform this comparison was to join the lists of articles from all four reviews and assign a “yes” or “no” value to each one on a matrix, in order to find out which article was reviewed by whom. The result allowed the identification of overlaps on the literature as well as the gaps and the “distance” between the review articles, and some insights according to different criteria will be discussed. This classification for each review paper has been added to the final review matrix, which can be viewed in Appendix B.

It is interesting to note that, from the 175 articles considered in this section, only five were cited by all four reviews, namely Ceder and Wilson (1986), van Nes et al. (1988), Partha Chakroborty and Wivedi (2002), and W. Fan and Machemehl (2006a, 2006b). Despite the differences in scope and divergences in focus among the reviews, these articles were considered by all authors. The papers by Ceder and Wilson (1986) and van Nes et al. (1988) may be considered seminal works as they have set a standard for the research performed and have been cited extensively. They have also performed early surveys of the state of the art at the time they were published, which has made these works interesting points of entry for potential researchers throughout the years. W. Fan and Machemehl (2006a) also performed a non-systematic literature review at the time as a way to support their own research (as previously summarized), and its inclusion in a systematic review is therefore important. These articles are, however, too few considering the volume of research that has been published in the last four decades, which indicates the lack of consensus on the selected literature that has previously been mentioned.

On this list of articles, 24 others were found to have been cited by three of the four reviews. Some interesting considerations can be taken from the analysis of this list, such as the fact that all of them were published before 2008 and that all except two were cited by Guihaire and Hao (2008). It is also visible that the greatest overlap among this set of articles is between Guihaire and Hao (2008) and Farahani et al. (2013), while Ibarra-Rojas et al. (2015) reviewed only 10 of these 24 articles.

Apart from the intersection between the literature chosen by each review, it is also interesting to analyse them one by one to understand the degree of “exclusiveness” that each review presents, i.e., the amount of articles considered by each one that are not included in the others. The results, obtained through the analysis of the existing list, are presented in Figure 7.

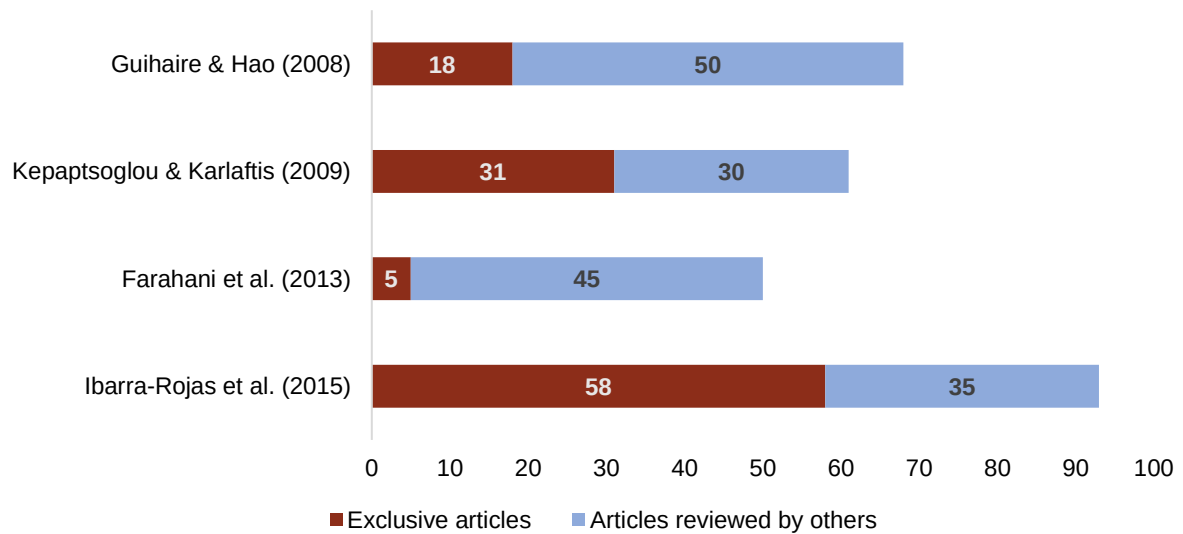


Figure 7 - Exclusive and non-exclusive articles for each review

This analysis allows for some interesting hypotheses about the literature to be considered; for example, the review by Farahani et al. (2013), while being the widest and most ambitious of the considered reviews, is more limited on the singular problem of transit network planning and design (as previously discussed), which may be shown by the smaller overall amount of papers considered on the subject and the tiny amount of original papers chosen – only five. The opposite may be said of the review conducted by Ibarra-Rojas et al. (2015), in that the scope of their analysis is narrower but deeper than the other authors, and 58 out of the 93 considered papers ($\approx 62\%$) were original as well as exclusive. This review also had the largest overall number of papers reviewed on the subject, as it considers more sub-problems than any previous authors (also taking into account that the papers reviewed by Farahani et al. (2013) that were not related to transit network planning were filtered out of this analysis). This review also has the characteristic of being the most recent of the four; while Farahani et al. (2013) had only two exclusive articles that were published after the previous reviews, Ibarra-Rojas et al. (2015) counts 44 exclusive articles that were published after 2008 – around 47% of the total considered – and 40 after 2009. It is evidently impossible for these articles to have been reviewed before their publication date, so the fact that this particular study has a majority of exclusive articles may be explained by its recency; however, it also adds 14 articles that were not reviewed by any previous author despite already having been published.



Figure 8 - Overall exclusive and non-exclusive articles

Even more dramatic is the consideration that, when taking into account all 175 identified papers, the majority of them (64%) were reviewed only by one author. This means, as shown in Figure 8, that only 63 articles were reviewed by more than one author, which, given the extensive amount of thematic

overlap between them, raises questions on the globality of the existing reviews (despite the previous consideration of them not being contemporaneous). This also reinforces the need for further reviews on the subject, as there may be some analysis that can be performed on the existing gaps among the previous reviews.

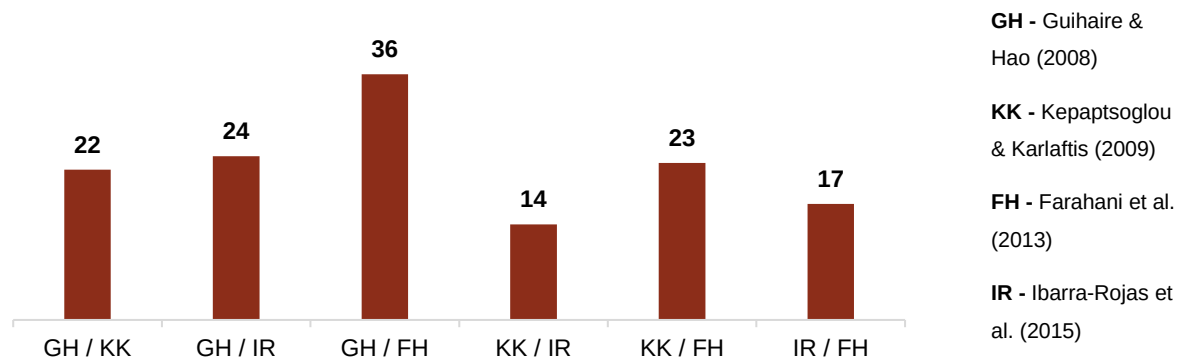


Figure 9 - Articles in common between pairs of reviews

After analysing the reviews grouped by four, three, and individually, the other possible combination to be considered is an analysis by pairs, as shown in Figure 9. It represents the number of articles that appear in both reviews for each pair, including both the articles that were exclusively considered by both and the ones that feature in more reviews apart from the pair. This may be interpreted as a measure of the overlap between the existing reviews. It is visible, for example, that Ibarra-Rojas et al. (2015), having the most exclusive articles (as shown in Figure 7), also appears to have the least amount of overlap with previous similar studies. Guihaire and Hao (2008), however, appears to have the most overlap with all others, which can be attributed to it being the earliest of the four and cited by most.

This analysis has compared the structures, methodologies, and databases that characterize the existing literature reviews. It has also attempted to find some of the fragilities they show on these three parameters, in order to both justify the need for a more comprehensive and global review of the network planning problem and to inform the construction of a more robust methodology. Nonetheless, there are also very positive aspects in each previous review that will serve as a basis for the present study, albeit reinterpreted. This construction of a new literature review and the way the previous ones are integrated will be discussed in the following chapter.

3

METHODOLOGY

3.1. SELECTING A METHODOLOGICAL APPROACH

The main goal of this study, as stated before, is to understand the BNDP from the point of view of existing research. This work approaches this objective through the construction of a literature review, systematically reading and analysing the existing research and then drawing conclusions from their comparison. Through a process of categorization, the literature itself becomes data – the input for the analysis that ultimately provides insights.

However, the path to achieve this was not straightforward; the validity of a literature review as a research methodology depends heavily on the careful construction of a robust method. In order to mitigate bias and allow the reader to verify the results, the process and criteria that lead to the final review need to be clearly defined and well reported (Toronto & Remington, 2020). To improve the results' accuracy and trustworthiness, the author must define a strategy and a set of guidelines and follow them correctly to develop the review in a comprehensive manner (Snyder, 2019).

An initial survey on established literature review methodologies was performed in order to construct the strategy for this study. It is interesting to note that most of the found applications of these methodologies come from the field of medicine and nursing, although there are also some examples of application in fields such as management, marketing and psychology, such as, respectively, Tranfield, Denyer, Smart, Goodhue, and Thompson (1995), Baumeister and Leary (1997), and Palmatier, Houston, and Hulland (2018). In the first two fields, the expansion of evidence-based practice has led to a multiplication of studies that employ literature review methodologies in the analysis of clinical cases for the formulation of theories and practical applications; in turn, a variety of methods to perform these analyses has emerged in order to better meet the specificities of each study. These methods are robust but there is some degree of overlap and confusion in their specific definition (Toronto & Remington, 2020). However, there seems to be a spectrum of methodologies ranging from simple to complex that may be applied; a succinct summary of some of these will be presented in the next paragraph.

The **narrative review** is a simple methodology that consists in the summarization of the relevant literature on a topic without a systematic approach, allowing the author to present an overview on the subject with limited synthesis (Toronto & Remington, 2020). It is a procedure that does not require a pre-defined plan or research question, gathering information as new articles are found. An **integrative review** is a more structured approach, where a narrower research question is required and there is a construction of theoretical framework; these kinds of reviews can provide synthesis on not only empirical studies but also methodological or theoretical studies (Toronto & Remington, 2020). On the other end of the spectrum, a **systematic review** is a more rigid approach that has a very clearly defined framework and a narrow and specific research question, allowing robust conclusions to be taken from synthesis. This

requires a quality assessment of the considered literature as a criteria for inclusion, given that the quality of the conclusions depends on the quality of the data (Ravindran & Shankar, 2015). Another approach that is subordinate to a systematic review is a **meta-analysis**, where the quantitative results of each study is integrated and processed through statistical procedures; this approach is followed, for example, in the medical field, where numerical results of clinical case studies that deal with the same research issue can be extracted and compared directly. Somewhere between a narrative and a systematic review is the **semi-systematic review**, which slightly overlaps with the first but has more well-defined structures. It allows for broader research topics and more flexible analysis, while its procedures require more adaptation to the research being performed (Snyder, 2019).

These methodologies have varying degrees of strictness around the structure that they propose, but the main takeaway is that a good review requires:

- (1) a well-defined research question or research problem;
- (2) systematic criteria for searching and including or excluding information;
- (3) a robust method for analysis and classification;
- (4) a well-constructed synthesis of the reviewed literature;
- (5) a good communication of both the steps taken (to allow verification and replicability) and the results obtained in order to have an impact.

In this particular study, the collected “data” is not quantitative in nature, i.e., there aren’t numerical results that can be compiled and analysed to create a model, and the nature of the studied topic is methodological and not empirical; thus, a meta-analysis is not possible, as it requires quantitative data for the statistical models to be applied (such as clinical reports). Another limitation regarding the most rigorous methodologies is the wider research question that motivates this study; the definition of a narrow focus would go against the objective of understanding and identifying the many different approaches that have been taken on this subject. It would be paradoxical to guide the review by issues that could only be identified through the careful reading, analysis, and comparison of the literature – i.e., constructing the review itself. The solution considered in this study was then to identify the main issue, while more specific research questions would arise during the work itself through the process of reading the selected literature.

These considerations led to the conclusion that a methodology closer to a **semi-systematic review** would be more adequate for the present study, as the sources are composed of methodological research papers and the data is inherently qualitative. The structure of this review is then divided in five steps, as shown in Figure 10.

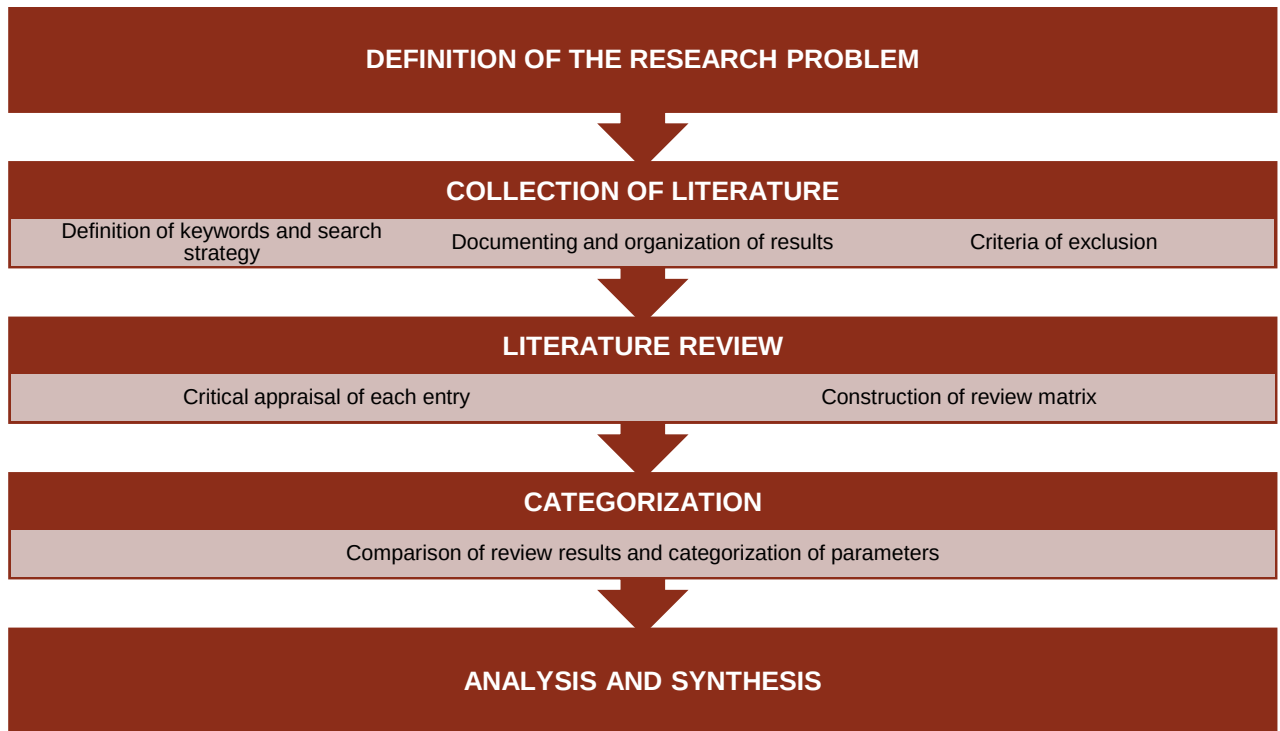


Figure 10 - Structure of the proposed literature review process

The first step consists of the **definition of the main research problem** for the literature review. In this case, the research is focused around a problem and not a specific question; although this presents a difficulty for a narrower and more specific analysis, it is considered in this study that a more rigorous definition of the thematic scope of the review is sufficient for the goals that were set in the beginning. The definition of the problem was discussed in the first chapter.

The next step deals with the **collection of the literature** that will serve as a basis for the review. It was necessary in this phase to define a search strategy and the sources that would be used; for the search, the definition of keywords and search queries is necessary to use search engines more efficiently. It is also necessary to define criteria for the inclusion or exclusion of specific works in order to maintain a focused approach to the research subject. In this chapter, these sub-steps will be discussed, as well as the final results of this process (which are presented in Appendix A and Appendix B).

The two steps that follow – **review and categorization** – are not entirely sequential – they form an iterative loop that should be carried almost simultaneously. The reading and appraisal of the literature is organized in a review matrix, which construction is analysed in this chapter. Simultaneously, this process is accompanied by a constant comparison of results that allows the identification of common themes and characteristics in the considered studies; this leads to the development of categories that will serve as the main basis for the analysis and eventual synthesis. The final results of this process and the definition of the categories will also be presented in this chapter.

The final step of the process, which corresponds to the **analysis and synthesis** of the considered literature, will be presented and discussed in Chapter 4.

3.2. COLLECTION OF LITERATURE

As previously discussed, after the definition of the research problem, the step that followed was the collection of the papers to be analysed in the review. Typically, the search would begin with the definition of search terms, appropriate databases and clear inclusion or exclusion criteria; this kind of search would yield a large number of articles on the first phase, and these elements would be crucial to guarantee that the review stays focused on the subject and exempt from bias.

However, in this particular case, there were already four comprehensive reviews in existence when this work began, as discussed in Chapter 3. An important conclusion of that chapter was that these authors already produced considerable databases for their own reviews, albeit with different methodologies, criteria, and focus. It was shown that their collection converged consensually on a small number of papers, but a large part of the considered literature was reviewed by at least two of the authors; in many cases, they were reviewed by only one author but they met the same criteria for inclusion as the consensual papers. It would not have been reasonable to ignore this existing body of literature, neither to start a new search from scratch when the problem had been reviewed four times before, even with different thematic focus. It was thus considered in this study that a good starting point to collect the literature to be analysed would be to compile all the articles reviewed by the mentioned authors. This way, the present review could achieve a wider view of the problem from the start, while also building upon an extensive database already compiled by the previous authors.

However, it would not be sufficient to only consider these, as there may have been some works that were not considered by the previous authors that could be relevant to this analysis. Furthermore, the last global review at the time of the present study was published by Ibarra-Rojas et al. (2015). and further papers on this subject may have been published in this five-year span. So, in order to build a database of literature, there was a need to survey more works related to this problem in the first approach.

It is also interesting to note that Farahani et al. (2013) reviewed the problem from a wider perspective than the other authors, including road network design problems and multimodal network design problems, as discussed in Chapter 2. Consequently, many of the articles considered in their review were outside the scope of this work and were not included from the start. However, they separated their analysis by problem type, which allowed the selective extraction of only the articles relevant to this study.

3.2.1. SEARCH METHODOLOGY

The search strategy defined to find new works to be reviewed started with the definition of keywords that enable a more guided survey. The choice of these keywords was guided by the structure of the problem identified in Chapter 1, i.e., the main overarching issue is the *network design problem*, which has a subdivision called the *transportation network design problem* (note that the term *transportation* is mostly interchangeable with the term *transport*, due to differences between American English and British English). Within this problem (which considers all kinds of transportation networks) there is a subset called *urban transportation design problem*, as defined by Farahani et al. (2013), which contains the specific transportation design problems in cities. As the problem regarded in this study contemplates only public transport modes (specifically buses), it required the addition of keywords such as *bus*, *public transport*, *public transportation*, or *public transit*. In order to broaden the analysis, as some works may have only regarded a specific aspect of the BNDP, further search terms such as *frequency setting*, *scheduling*, *timetable*, *driver scheduling* and *vehicle scheduling*, although these were only added in a later and more detailed search when the other keywords were fairly well used. These keywords are summarised in Figure 11.

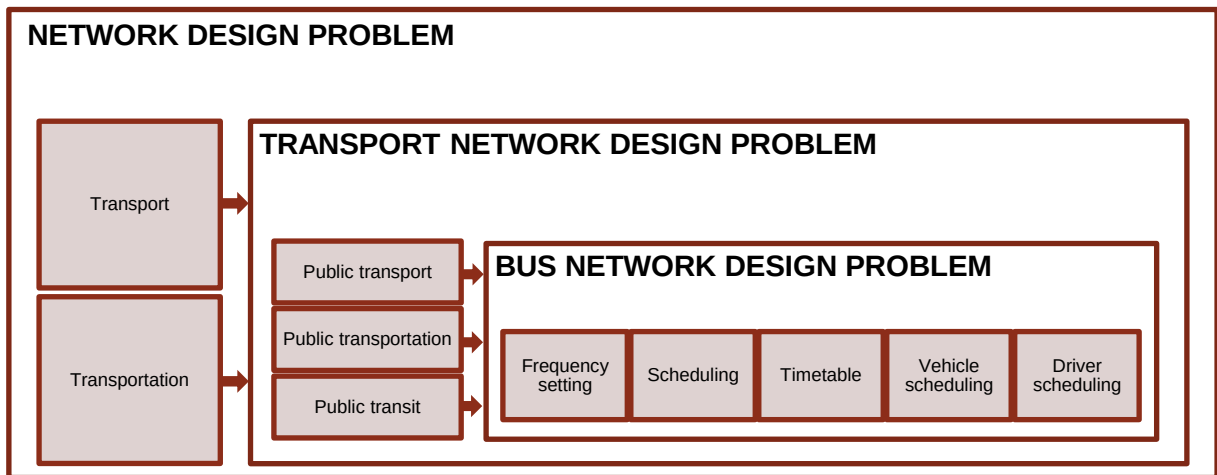


Figure 11 - Keyword definition for the literature search

The literature extracted from the existing comprehensive literature reviews, as previously discussed, was organized using Mendeley's reference manager software before the search was performed. This allowed new entries to be compared to the existing ones in order to avoid duplication. Also, the software was used to construct the database, allowing it to be exported in BibTeX format; using JabRef software, it was possible to convert the database into a spreadsheet file that served as an input for the review matrix.

An initial, non-methodical search was done through the Google Scholar search engine, which yielded some interesting results as a starting point. Further, a more rigorous search was made through the Scopus engine, which allowed a better use of the defined keywords and Boolean operators to refine and direct the queries. The engine also allowed a search by author, where some significant (recurring) authors were selected in order to view their full published work on the platform and also the subsequent works that cited them, expanding the search procedure beyond the keyword search. These articles were then added to the Mendeley database and organized.

3.2.2. INCLUSION AND EXCLUSION

Through this methodology, a large database was constructed, with the final list containing 247 articles. Although a pre-screening of found articles (by reading the title and the abstract, or even quickly scanning its contents) allowed for some filtration of works that did not obviously meet the search criteria, many were considered ambiguous as to their relatedness to the problem in this study, and were included in this list. For this reason, it was necessary to filter the existing studies according to inclusion criteria, as some of the works that were found in the previous step may have been off topic. It was also possible that the body of studies extracted from past reviews contained ineligible works; thus, the whole list was scanned and filtered according to the set criteria (figure 12).

For the definition of these criteria, the principle followed was to aim for a less restrictive rule, as it was considered that the research problem could have a better analysis if the selected literature represented a plurality of points of view and motivations, as the main focus is on understanding the different approaches that were taken by researchers. Thus, the main criterion selected was the relatedness to the research problem, as defined in Chapter 1; this meant that studies were to be eliminated from the review if their focus was not the design of bus networks in its strategic, tactical or operational dimension. Studies that concerned multimodal networks (i.e., the interaction between private cars and public transport),

road network design or traffic management solutions – even if they implied the use of public transport but did not make it the main focus – were to be discarded from the analysis. Also, studies that concern operational strategies for buses without the determination of schedules or vehicle and driver assignment were discarded. Another criterion for removal was applied for studies that discussed the problem or an approach to it but did not present a methodology or a model, the variables considered, or the application results; those cases could not fit in the analysis if the main parameters to be appraised were not present.

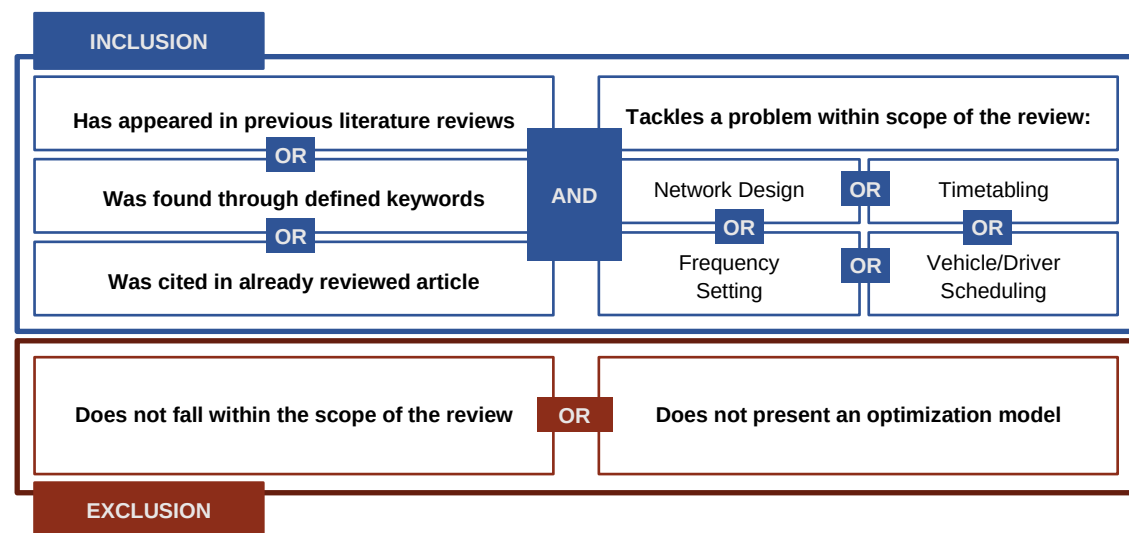


Figure 12 - Summary of inclusion and exclusion criteria for the review

One other criterion that remains a limitation of this work is the access to the full document – only full studies were considered for review, as extracting information from abstracts or from the existing reviews was considered to be unmethodical. This meant that, even if the study had been reviewed by past authors, if the full document was not available it would have to be discarded from the study. Unfortunately, it was verified that it was not possible to gain full access to a number of articles previously identified², especially older articles that were not available online – their references can be found in Table 2.

² It is relevant to note that this dissertation was developed during the COVID-19 pandemic, and because of the many lockdowns that were in place during this time the access to physical resources in libraries or in campus was severely restricted.

Table 2 – Articles not included due to lack of access to full document

Author(s)	Year	Title	Reviewed by:			
			GH	KK	IR	F
Patz	1925	Die richtige Auswahl von Verkehrslinien bei großen Straßenbahnnetzen	Yes	No	No	yes
Holroyd	1967	Optimum bus service: A theoretical model for a large uniform urban area	No	Yes	No	No
Byrne & Vuchic	1971	Public transportation line positions and headways for minimum cost	No	Yes	No	No
Sonntag	1977	Linienplanung im öffentlichen personennahverkehr	Yes	No	No	Yes
Hasselstrom	1979	A method for optimization of urban bus route networks	Yes	No	No	Yes
Hasselstrom	1981	Public transportation planning — A mathematical programming approach	Yes	Yes	No	Yes
Koutsopoulos	1985	Determination of Headways as Function of Time Varying Characteristics on a Transit Network	Yes	No	No	No
Pape et al.	1992	Entwurf und implementierung eines linienplanungssystems für den busverkehr im pnv unter einer objektorientierten grafischen entwicklungsumgebung	Yes	No	No	Yes
Chakroborty et al.	1997	A genetic algorithm-based procedure for optimal transit systems scheduling	Yes	No	Yes	no
Russo	1998	Transit frequencies design for enhancing the efficiency of public urban transportation systems: An optimization model and an algorithm.	No	Yes	No	No
Dhingra and Shrivastava	1999	Modelling for coordinated bus train network	Yes	No	No	No
Ceder & Tal	2001	Designing synchronization into bus timetables	No	No	Yes	No
Cipriani et al.	2006	A multimodal transit network design procedure for urban areas.	No	No	No	Yes
Ibarra-Rojas et al.	2015	Multiperiod synchronization bus timetabling	No	No	Yes	no

Other studies that were either part of the existing body of literature from the existing reviews or were found during the search that was conducted were found not to meet the established inclusion criteria upon reading; in total, 14 such articles were found. The nature of their divergence from the established criteria is varied, and as such they are presented in Table 3 with the justification for their exclusion.

Table 3 – Articles excluded from final review

Author(s)	Year	Title	Justification for exclusion
Baaj and Mahmassani	1992	Artificial Intelligence-Based System Representation and Search Procedures for Transit Route Network Design	Not in scope, directed at further AI-related research
Xiong and Schneider	1992	Transportation network design using a cumulative algorithm and neural network	Not in scope, directed at road network design problem
Shih and Mahmassani	1996	A design methodology for bus transit networks with coordinated operations	There is a more recent publication of the same study by the same authors (Shih et al., 1998)
Bussieck	1998	Optimal lines in public rail transport	Not in scope, directed at railway network planning
Chen and Yang	2004	Stochastic transportation network design problem with spatial equity constraint	Not in scope, directed at road network design problem
Chiou	2005	Bilevel programming for the continuous transport network design problem	Not in scope, directed at continuous network multimodal design problem
Bartholdi and Eisenstein	2012	A self-coordinating bus route to resist bus bunching	Not in scope, directed at control of bus operations to avoid bunching
Tu et al.	2014	The study of bus transit network design methods for different sized cities	No model, summary of various route design methodologies and their suitability to different sized cities
Chao	2017	Study transit network design for Rivera of Uruguay	No model, critical revision of Mauttone & Urquhart (2009)
Chuang	2017	Study for transportation system of urban area of Rome	No model, critical revision of Cipriani et al. (2012)
Klumpenhouwer and Wirasinghe	2018	Optimal time point configuration of a bus route - A Markovian approach	Not in scope, directed at operational bus control and holding strategies
Shafahi et al.	2018	SpeedRoute: Fast, efficient solutions for school bus routing problems	Not in scope, directed at operational bus control and routing strategies
Dai et al.	2019	A predictive headway-based bus-holding strategy with dynamic control point selection: A cooperative game theory approach	Not in scope, directed at operational bus control and routing strategies
Leich and Nagel	2019	Improving speed and realism of an evolutionary minibus network design process	No model, improvement of existing software, not specifying objectives, variables, or constraints

3.3. REVIEW MATRIX AND ANALYSIS METHODOLOGY

3.3.1. INITIAL REVIEW MATRIX

After performing the steps previously described, the final list was composed of 217 articles for review. The next step was to read each article and summarize the important information in each systematically; in order to be able to do this, the chosen strategy was to construct a review matrix. Each line would correspond to an article, and each column would contain a parameter of analysis that is extracted from it. This procedure gives structure and uniformity to the analysis of the literature, as each article is reviewed through the same lens and the parameters are directly comparable.

The question that follows is what parameters to designate to each column, i.e., what should be the main information to be extracted from each article. Some parameters are trivial, such as the **author(s)**, **year**, **title**, and **publication**; this is the information extracted directly from Mendeley, which allows the user to export a library that can be converted into a spreadsheet format. The other parameters are not so straightforward but pivotal nonetheless – their configuration dictates the type of analysis and eventually synthesis that can be made in the review, hence they should be carefully constructed.

As previously discussed, this stage of the analysis is meant to be an *iterative* process. One of the issues at the start of this study was the author's insufficient knowledge about the subject, and one of the main motivations to perform this review was not only to attempt to create new knowledge from the analysis of the literature but also for it to be a learning process. This constraint meant that, inevitably, the starting point for the structure of the analysis would be different from the final result, as more information and constant comparison and questioning would allow a refinement of the parameters. This was a limitation for the study, as it would become more time consuming and prone to errors; but it also meant that there would be less probability for bias, as the structure of the analysis would evolve from the literature itself and not be forced to fit a pre-conceived structure.

However, this process required a starting point for the construction of the review matrix, as some initial parameters were necessary to begin the classification. For this objective, the analysis of the previous literature reviews described in Chapter 2 was a good inspiration, as most of the criteria they proposed for the classification of the review matrix were also aligned with the objectives of this study. The review of the **solution methods** was unanimous in all four reviews, as well as the identification of the main **objectives** of each paper. The definition of **constraints** and **decision variables** was, however, not consensual among the reviews, as all authors classified the former while only Kepaptsoglou and Karlaftis (2009) classified the latter. In the present work, it was considered that both were equally important to understand each approach to the problem, as when viewed together these parameters provided a clearer vision of the inputs, outputs, and overall structure that each author(s) proposed. This consideration also indicated a gap in the previous reviews, as none of the authors considered the constraints and the decision variables of each problem together.

The **case application** parameter was also considered to be central in the review, as one of the main questions identified in the beginning of the study was on the disparity between theory and practice in this field, i.e., understanding if the majority of articles published on the subject were theoretical studies directed at the advancement of techniques and solution methods or if they were aimed at practical applications. Understanding the differences between these studies, both in parameters and approach, was also an objective of this study. This was previously studied by Guihaire and Hao (2008) and Ibarra-Rojas et al. (2015) (and, to a lesser extent, by Farahani et al. (2013), which only considered a select amount of articles with real cases), as can be seen in Table 1 in the previous chapter. The first authors represented these cases by a very short description of their application, while the second authors followed a more rigorous classification, categorizing the cases as “real” (the model is applied to a real

network), “test” (where random sets are generated based on real circumstances), “example” (simplified networks, real or artificial), and “benchmark” (solution is tested on models previously established in literature). The initial classifications considered in this study were inspired by the latter, as the classification was divided in **real**, **example**, and **benchmark**, with studies that had no application being classified with **none**. Another aspect that was considered to be important and was included in the analysis was the definition of the size of the database that was used, particularly in real cases; this was relevant because the real applicability of the proposed methods may depend on the size of the network that it is able to calculate, and also because cities of different sizes have different specificities that should be taken into account when designing a bus network. Thus, two additional columns were added to the matrix, where one identified the real-world location where the data was based on and the other provided a measure of the size of the studied network.

The **problem definition** category that was studied by Guihaire and Hao (2008) was not considered in the present work, as it was based on the nomenclature and organization of the problem proposed by these authors (that can be seen in Figure 2). It was instead replaced by a definition of the **problem category** based on the five step model referenced earlier, where the subject of each study was evaluated according to whether it covered one or more of these steps (network design, frequency setting, timetabling, vehicle scheduling, and driver scheduling). The objective was to find the problem definition through the analysis of problem categories, arriving at it through the evidence found from the literature review.

In summary, the categories on each column of the initial review matrix consisted of four descriptive parameters (publication, year, author(s), title), the main optimization objectives (objective function), the parameters (constraints and decision variables), the solution method, the application (application type, network size and location), and the problem category. The comparison with the previous authors can be seen in Table 4, which is adapted from Table 1 from Chapter 2.

Table 4 – Comparison of the adopted parameters for the review matrix with previous authors

	Problem definition	Problem category	Objectives	Constraints	Decision variables	Solution method	Case appl.	Network size and location	Other
Guihaire & Hao (2008)	●		●	●		●	●		
Kepapstoglou & Karlaftis (2009)			●		●	●			●
Farahani et al. (2013)			●	●		●			
Ibarra-Rojas et al. (2015)			●	●		●	●		
Present study		●	●	●	●	●	●	●	

The review process began by reading each of the articles in the final list and filling in each of the previously described parameters. Initially, this was done through text, as the review matrix worked as a support to summarize the main aspects found in the papers as they were read. In some cases, this summarization required some degree of interpretation, as some articles did not clearly state the parameters they employed in their studies. In the other cases, where the authors described their model more explicitly, the terminology applied to summarize these parameters was intentionally as close as possible to the

original, although the degree of clarity also varied. This presented an additional difficulty in that the same concept had different names in different papers, or, as the opposite, concepts with the same name had different meanings according to the context. These inconsistencies created challenges to the ability to synthesize the information present in each paper, which also demanded some interpretation by the author; this constitutes a weak point of the present study, as this interpretation also may have led to inconsistencies in the review itself.

3.3.2. EVOLUTION OF REVIEW MATRIX

As previously discussed, it was predicted by design that the parameters of analysis in the review matrix would naturally be adjusted as the knowledge on the subject was expanded and concepts were compared to each other. As such, the matrix and its configuration were always questioned during the review process, as outliers which did not fit on pre-established categories were found. The inclusion of these outliers was very constructive for the review, as they challenged existing preconceptions and added new information that was valuable, but their inclusion implied, sometimes, the adjustment of the evaluation criteria.

One example of this situation was found when evaluating the application cases. The simplified division between “real” and “example” started to become insufficient as many papers were considered to be on the grey area between the two. Some articles that included real cases were very grounded in reality and incorporated practical concerns in both their models and their conclusions, but others used real databases (albeit simplified) only to evaluate the performance of their algorithms; this raised the question of the validity of both being classified as “real” cases just because they used real data, although their methods and objectives were very different. The same could be said of cases that present simplified examples as demonstrations of their methods, in that some aim at practical applications (where, in some cases, the artificial networks could just be placeholders for future real applications) and others simply test theoretical computational performances of algorithms without intent to apply them in real life. For the sake of clarity and the usefulness of the analysis, it was necessary to rethink the framework for this classification

Another adjustment that was found to be necessary was the separation of constraints and decision variables into two different parameters. The identification of these two parameters together was difficult and confusing, as it made the division between what were inputs and outputs of the problem unclear. Considering them separately allows for a more adequate description of the decisions taken by each author to structure the problem and develop a model, while still allowing a synthesis to be made between them.

These adjustments were performed during the review process, and the need for them was identified as difficulties in classifying the articles appeared. These changes in the analysis criteria naturally required a revision of the articles that had already been studied, which led to some of them being read more than one time.

3.3.3. FINAL PARAMETERS AND DEFINITIONS

After the previously described process was concluded, the final result was a review matrix that contained a description of each parameter considered for all 217 articles; this matrix is integrally presented in Appendix A. This matrix included the classification of objectives, constraints, decision variables, and application type, as well as the methodology and information about the data applied in the case studies (as defined in Table 4).

This method of summarizing the gathered information through text led to a dispersion of the classification, as different authors either used slightly different names for the same concept or applied different parameters that were very close in function and meaning. Although many of these elements are common throughout the entire literature, many authors introduce small variations in the definition of their variables (either to simplify them or to increase the level of detail incorporated in their models), and these variations were reflected in the review matrix. The description of these parameters in text allows for the reading of specific information that was gathered on each of the studies; it was, however, not sufficient for more detailed analysis and comparison between these parameters.

The ability to synthesize and compare this information depended on the development of a systematic classification. For this end, the first step taken was to list all the different variants of each parameter that were found. The comparison of entries on this list allowed for their codification, i.e., the attribution of a “code” that grouped similar concepts into a category. This codification was performed various times, as the first attempts produced uneven results – some categories were too specific (which may have rendered them useless for a comparative analysis), while some were too wide (including sub-categories that were too different to be considered together). Overall, these categories tried to achieve a balance between a categorization wide enough to be comparable and analysable and the inevitable loss of granularity and accuracy that comes through generalization. As with the review itself, these final categories were also affected by some inevitable subjectivity that is inherent to the evaluation of these concepts; in order to clarify this process, it was considered to be important to present the definitions that were attributed to each identified category – these definitions are presented in the following entries in this section.

The results of this classification process were, as mentioned, the categories that will be defined in the following sections of this chapter. However, to be able to analyse and produce insights on the literature through comparison and synthesis (which will be discussed in Chapter 4), the results for each entry of the review matrix also needed to be classified individually according to this framework. The method employed to achieve this was to create a “translation” of each individual variant of the parameters into the defined categories; the “key” for this translation already existed as the result of the classification process. An auxiliary matrix was created where each column corresponded to a category, and they were compared with the existing text in the review matrix through this “key”, producing a “true” or “false” answer if the category existed or not in each entry. This “true” or “false” matrix allowed for the transformation of a text-based review into data that could be counted and compared.

The final visual representation of these results was inspired by the review matrix presented by Farahani et al. (2013) for the RNDP. It was obtained by placing a dot for each “true” value, which allows for an immediate evaluation of each entry in the review according to the parameters that it has used. This final matrix is presented in Appendix B. For the analysis in Chapter 4, this matrix was transformed into a binary matrix with 1 for “true” and 0 for “false”, which facilitated the analysis of the raw data.

3.3.3.1. Application type

The final definitions of the application type that were employed on the review matrix resulted, as previously discussed, from a need to construct a more systematic classification of this aspect. The analysis was divided into two axes: the realism of the data set and the focus of the conclusions.

The first axis is presented on the left of Table 5, and corresponds to the evaluation of the data that was used to perform the application of the model. If the case was constructed with actual data from real cities (if the authors explicitly described it as such) or with data which complexity was approximate to a real case, they would fall on the upper line of this table. If the data was constructed to present an example of the model's application, or if it was real but so simplified that it resembled a constructed case, it was classified on the lower line of the table.

The other axis corresponds to the two columns of Table 5, and measures if the focus of the model's application is on the actual solutions to the problem or only on the performance of the method. This was found to be a relevant measure of the realism of the models reviewed, as many articles, although presenting real (or realistic) data in their applications, only analysed their findings through the lens of the improvements of computational performance of the methods (usually through abstract metrics); classifying these cases as "real" would not be entirely true. These cases, whether they had real or constructed data, were classified on the right side of the table, while cases which focused on the practical application of their model would fall on the left side of the table.

Another special case was found that was deemed relevant enough to warrant its own category. Many reviewed articles presented benchmarks as tests of the models they proposed, using pre-established data from literature. These cases were classified specifically as "benchmarks" because, although their applications would usually fall on the "test" category, they were very similar (with most articles using the same benchmark and solving the same problem).

These categories intend to evaluate the degree of realism that the authors defined for their applications, and approximately where they would also fall on the "practical-theoretical" axis. This classification was, however, also subjective; even though these five categories allowed for a more systematic analysis, many articles were found to be on the "grey areas" between them. This classification also reflects the interpretation of the author, but nonetheless it offers a much more unambiguous picture than the previous classification, as the decisions are justified through the system that is illustrated in Table 5.

Table 5 - Definition of the application type classification

	Conclusions focus on solution and configuration	Conclusions focus on model and performance
Real data set	Real	Realistic
Constructed data set	Example	Test
Standardized data from literature	Benchmark	

3.3.3.2. Objective Function

The problem of designing and planning bus (and other transit) networks is inherently multi-objective, as previously discussed. The optimization of a network needs to take into account the sometimes contradictory objectives of the users and the operator, which has led to an interesting variety of optimization objectives in the existing literature. It was found during the categorization process that most of the identified variants were either directed at the benefit of the user or the operator, and their analysis was separated according to this division. The definitions presented in Table 6 are also organized this way. The quantitative results of the analysis were also divided into whether the objectives were directed at maximization or minimization of the relevant parameters, as is defined in Appendix B and in Chapter 4, but this division was not applied in the presentation of the definitions.

The main objectives of the model were, in most cases, clearly stated by the authors in each paper considered, which made their identification and subsequent classification easier than other parameters. Nonetheless, the dispersion of the nomenclature applied was also verified in this case, and there was some confusion at the different definitions that were found for the same concepts. For example, some authors used “travel time” as a synonym for total travel time (which included the waiting and/or the access time), while others considered it as only the in-vehicle travel time. The definitions presented in Table 6 attempt to clarify some of these ambiguities.

Table 6 - Definitions of objective function categories

USER	
User cost	The cost incurred by the passengers for a decrease in the system’s service level; its minimization represents the users’ interest in the optimization of the transit network. The overall cost is obtained through the attribution of costs to other minimization sub-objectives, such as travel time, waiting time or number of transfers.
Access time	The time taken by a user to access the network, usually defined by the walking time needed to reach stops (some exceptions also considers feeder buses and bicycles).
Travel time	In this case, travel time is used as a synonym for in-vehicle travel time , i.e., the amount of time a user spends travelling in order to reach their specific destination. It constitutes a measure of the directness and efficiency of the designed system and is often considered alongside waiting time and/or access time to minimize an average or total travel time.
Waiting time	The time a passenger needs to wait before boarding a vehicle. Can be the time required to complete a transfer (in transfer optimization problems) or the time between the arrival of a passenger to a stop and boarding.
Number of transfers	Amount of in-system transfers required to satisfy a specific O-D pair. Usually considered as a percentage of demand satisfied with one or more transfers, its minimization increases directness and reduces passenger discomfort.
Coverage	Minimization of unsatisfied demand, either geographically (by covering most OD pairs) or chronologically (by covering most trips throughout the day).
Potential transfers	Maximization of the number and quality of transfer opportunities in order to enhance network connectivity.
Welfare	Multiple criteria objective that maximizes not only user benefit but overall social benefit from the optimization, usually implicitly balanced with operator cost minimization.

OPERATOR	
Operator cost	The cost incurred by the operator for an increase in the system's service level; its minimization represents the operator's interest in the optimization of the transit network. It is obtained through the application of costs to various network parameters, such as route length or fleet size.
Fleet size	Minimization of the required number of buses for the operation of the designed network at the determined frequency. Used as a measure for operating cost
Load factor	Optimization of the load factor indicator (obtained by dividing passenger-kilometres by place-kilometres) as a measure of utilization of vehicles in the network, in order to minimize crowding and/or enhance profitability.
Deadheading time	Minimization of the amount of time the vehicles would run empty (no passenger service), either to/from a depot or in between line runs; the objective is the benefit of operator profitability as it aggravates operating costs without providing revenue.
Emissions	Minimization of global network emissions, measured from unit values applied to operational parameters and/or to a life-cycle analysis (that includes the construction of vehicles and infrastructure).
Profit	Maximization of operator profitability, being the inverse objective of operator cost minimization.
Ridership	Maximization of ridership potential for the network, obtained by optimizing the satisfaction of existing demand and/or potential demand.
Passenger flow	Different measure of line utilization optimized by balancing flows, aiming to avoid both overcrowding and underutilization.

3.3.3.3. Constraints

The constraints of each model that was reviewed were defined as the bounds that were imposed on them so that their outputs were more adequate with reality. They were considered either as bounds to the problem, setting minimum or maximum limits on specific parameters, or as physical constraints, where they provided a “skeleton” within which the model must operate. These physical constraints were also interpreted as the *inputs* to the model, which are required input variables that have to be “fed” to the model for it to work correctly.

Like the objective function, during the analysis and categorization of the constraints some thematic patterns were identified, and similar instances were grouped together. Four of these groups were identified: network constraints (which dealt with the physical constraints of the network topology and configuration), fleet constraints (related to its size, capacity, and operational characteristics), budget constraints, and demand constraints. Constraints that were not related to any of these categories were grouped under the “other” classification. This structure helped the analysis, as the resulting number of constraint categories was quite large; thus, the grouping of these categories gives more legibility to the gathered data.

Table 7 - Definitions of constraint categories

DEMAND	
Demand data	Estimation of existing demand through the collection and processing of ridership data on an existing network (commonly ticketing data).
Demand density	Spatial distribution of demand that can be measured within defined zones, correlating higher population densities with higher transit demand.
Demand function	Variable demand model that is depended on a function; can be stochastic (simulating demand variation probabilistically) or elastic (which function may be time-dependent or service-dependent, usually in bi-level models).
Demand matrix	Array of values of passenger demand for each origin-destination pair, in this case considered to be applied to a set of nodes. The values can be fixed or variable (when the problem considers demand elasticity).
Modal split	The share of total demand assigned to each mode, considered when the problem is multi-modal (i.e., when the model considers interaction between two transit modes such as bus and rail – multimodal problems that contemplate car use and traffic modelling are not considered in this study).
Passenger arrival rate	Number of passengers that arrive at a specific station in a given amount of time. Applied as continuous function that models demand independently of origin and destination
FLEET	
Average speed	The average speed of vehicles in the network – applied as an input to calculate travel time or as an indirect measure of congestion in an existing network.
Vehicle capacity	The capacity of each bus (or other mode, such as urban rail) given as a constraint of the capacity of an existing or hypothetical fleet.
Fleet size	Represents either the fixed number of available vehicles (for problems that do not determine fleet size) or an upper or lower limit to the optimized fleet size (representing cost constraints).
Dwell time	The amount of time a vehicle can spend stopped at a station; can either be a fixed requirement or an interval that sets minimum and maximum values.
BUDGET	
Budget constraints	Pre-determined limits on operator costs given by a maximum available budget.
Subsidies	Input of maximum available subsidies as a constraint to profitability.
Unit costs	Monetary value attributed to a unit of a certain variable in order to model costs. Usually applied to operator-focused variables (such as vehicle operating costs or driver hourly wages) and user-focused variables (such as the cost of user time to penalize longer travel and waiting times).

NETWORK	
Existing frequencies	Input of already implemented line frequencies as a constraint for optimization problems.
Existing network configuration	Input of existing lines and stops already in operation.
Frequency bounds	Minimum and/or maximum values of the frequency that can be assigned to each line. Can be a feasibility constraint or a policy requirement.
Existing schedules	Input of already implemented schedules as a constraint for optimization problems.
Network configuration constraints	Various limits imposed on the network configuration solution as feasibility constraints, such as minimum or maximum route length, number of stops, number of lines, and number of zones.
Network structure	Input of the physical structure of the network before the lines are modelled, such as a set of nodes and arcs or the existing road network and/or existing stops.
Travel time matrix	Array of predicted (fixed) travel times between nodes in the network.
OTHER	
Driver shift constraints	Policy requirements for driver shifts, such as maximum driving time, maximum overtime or pausing times.
Emissions	Input of vehicle emission factors applied to operational parameters (such as vehicle-km or vehicle-hours) to determine the global emissions of the network.
Load factor constraints	Upper or lower bounds applied to the value of the network load factor; minimum requirements represent a network feasibility constraint and maximum values limit vehicle crowding.

3.3.3.4. Decision Variables

From the categorization process previously described, 12 separate decision variables were identified. Through the definitions adopted in this study, the decision variables are very interconnected with both the objective function and the problem type, as they represent the main parameters through which the authors evaluate their results. They were, however, more difficult to identify than the objective function, as they were usually embedded within the model and not explicitly stated. In these cases, the path that was followed to identify them was to examine the results and the discussion that each author presented and find the main outputs of the problem that were discussed, considering them as the main decision variables that the authors intended for the problem. In this case, unlike the previous parameters, the categories obtained were fewer and did not justify their division into meta-categories, and the analysis was performed on the integral list of these variables (table 8).

Table 8 - Definitions of decision variable categories

Departure times	Determination of schedules for lines (starting times) and stops (arrival and departure time at each stop).
Driver shifts	Generation of driver schedules compatible with line schedules, in some cases assignment of drivers to specific lines and vehicles.
Dwell time	Time vehicles spend stopped at a station for passenger boarding and alighting.
Fares	Determination of optimized value of fares to be applied on the network or on each line.
Fixed cost	Determination of implementation costs of the network, such as construction costs (where the problem contemplates construction of infrastructure) or other investments required to set up the line.
Fleet size	Determination of the required number of buses for the operation of the designed network at the determined frequency.
Frequency	Number of vehicle departures per unit of time on a line.
Network configuration	The topology of the optimized network, including the number and shape of lines and the sequence and/or location of stops.
Operating costs	Determination of overall running costs of the network, measured as a sum of several components (such as fuel costs, staff costs, vehicle maintenance, or other variable costs).
Ridership	Assignment of passengers to routes or trips; can represent the simulated number of passengers assigned or a measure of vehicle loading.
Vehicle assignment	Assignment of vehicles to lines and depots.
Vehicle capacity	Determination of adequate vehicle capacity for each line (uniform or mixed).

3.3.3.5. Analysis structure

The final review matrix, as was mentioned previously, was organized according to these parameters that have been defined. These parameters, when considered together, show the layout of the main functional parts of the BNDP that have been identified. They form a structure that guides both the review and the subsequent analysis that may be performed on the data obtained.

This structure, summarized in Figure 13, shows the relative organization that is proposed for each parameter; it is, along with the previous definition of all used variables, a key to understand both the presented review matrix (in Appendix A and Appendix B) and the analysis that will be developed in Chapter 4.

Objectives	User	• User cost • Access time • Travel time • Waiting time • Number of transfers • Coverage • Potential transfers • Welfare
	Operator	• Operator cost • Fleet size • Load factor • Deadheading time • Emissions • Profit • Ridership • Passenger flow
Constraints	Demand	• Demand data • Demand function • Demand matrix • Modal split • Passenger arrival rate
	Fleet	• Average speed • Vehicle capacity • Fleet size • Dwell time
	Budget	• Budget constraints • Subsidies • Unit costs
	Network	• Existing frequencies • Existing network configuration • Frequency bounds • Existing schedules • Network configuration constraints • Network structure • Travel time matrix
	Other	• Driver shift constraints • Emissions • Load factor constraints

Decision variables	Departure times	Driver shifts	Fixed cost
	Dwell time	Fares	Fleet size
	Frequency	Network configuration	Operating costs
	Vehicle assignment	Vehicle capacity	
Application case	Real	Realistic	Example
	Test	Benchmark	None (NA)
Problem category	Network design	Frequency setting	Timetabling
	Fare setting	Vehicle scheduling	Driver scheduling

Figure 13 - Proposed structure for the analysis and the review matrix

4

RESULTS AND ANALYSIS

4.1. ANALYSIS OF THE FINAL REVIEW MATRIX

Following the methodology described in the previous chapter, the final review matrix was obtained through a dynamic process. This way, the parameters and the classification would evolve with the expansion of analysed literature, as more knowledge on the subject was accumulated. Naturally, this also meant that the review matrix could always be further improved, even indefinitely; thus, it was necessary to make a decision to stop the analysis at a point where it was deemed acceptable. The final matrix that is integrally shown in Appendix A and Appendix B represents a crystallization of this process rather than a finished product; nonetheless, its final form is very close to the objectives that were set in the beginning.

The information presented in this matrix can, in itself, be the main result of the work developed for the present study, as it shows a systematic classification for each selected paper. It identifies the objective function (minimization or maximization), the constraints, and the decision variables present in each solution, which, as previously discussed, constitute the main "working parts" of the optimization models. It also classifies the methodologies and the applications of the model - whether the articles present real case studies (more grounded in practice) or simpler theoretical tests and numerical experiments, and other classifications in between. These parameters, defined in the previous chapter, present a solid image of each paper, although many details are naturally lost in this necessary simplification.

The review matrix is also divided in two modalities that represent two different steps in the analysis. As described in the previous chapter, the first phase of the review was performed simply by summarizing the main aspects of each parameters through text, along with some observations that were deemed to be relevant; the results of this step are presented in Appendix A. These written descriptions were later compared and grouped into classes and presented in a binary matrix where each dot represents a "yes" or "no" value for each paper, representing if that particular variable is present or not in each one. This binary representation of the data was accompanied by the construction of definitions that grouped similar concepts, allowing for a better synthesis of the main working parts of the bus network design problem. The definitions presented in Tables 6, 7, and 8 in the previous chapter provide context to the classifications that are shown in Appendix B.

4.2. DESCRIPTIVE ANALYSIS OF RESULTS

The process previously described that turned the codification of the text-based review matrix into a "yes" or "no" matrix for each category allowed for these categories to be turned into binary variables. By simply translating the existing dots into 1 for "present" and 0 for "not present", it would be possible

to treat this data numerically and gather both descriptive and comparative results about the selected literature. This section presents the results for the analysed parameters through this descriptive lens.

4.2.1. CHRONOLOGICAL ANALYSIS

The first descriptive parameter on the literature that was considered was the date of publication. The results of summing the papers by year is presented in Figure 14, showing the results from 1967 to 2020. It is visible that, in the earlier years considered, the scientific production on the subject was steady but not particularly voluminous, with one or two articles being published almost every year. In the 21st century, however, the production accelerated greatly, as there was a sharp increase in the amount of papers after 2001. It is also possible to see that, in this century, there were three separate “waves”: one from 2001 to 2007, another from 2011 to 2016, and lastly the most recent one from 2018. These “waves” show that there have been significant breaks in production of literature on the subject – the most significant of which between 2016 and 2017, with only 3 papers found from those years. Conversely, some of the recent years were also the most productive, with 2014 having seen 18 papers published on this subject, and 2019 and 2020 having 21 papers combined (considering that many papers published in 2020 may have been ignored in this study as the collection of literature stopped in the first trimester).

It is relevant to note that these results may also be influenced by the methodology followed to collect the literature for this review, as many articles in the period before 2015 were included from the previous existing literature reviews, and most of the additional articles that were found were from the period since 2011. This means that there may be a bias towards more recent articles, as modern search engines have more difficulty in finding older articles than recently published or more cited ones.

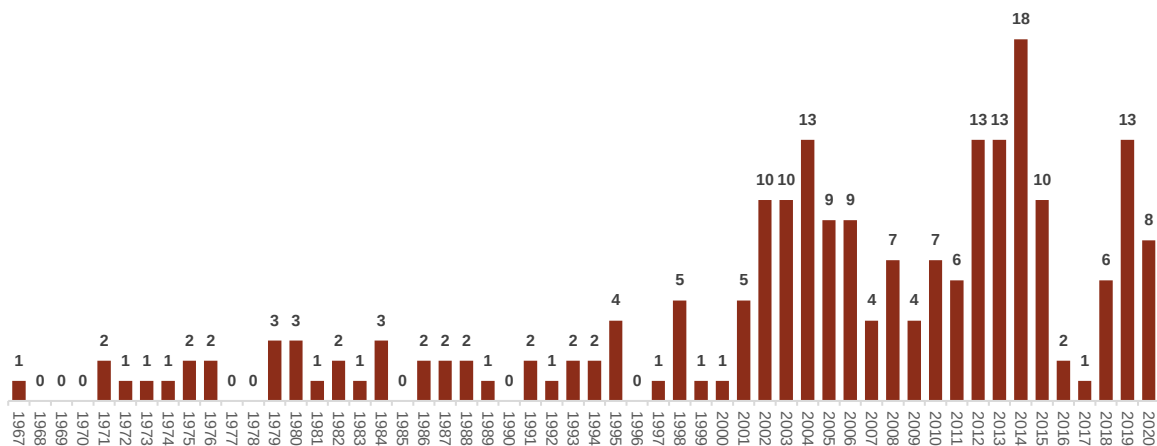


Figure 14 - Number of selected articles by year of publication

4.2.2. APPLICATION TYPE ANALYSIS

Of the four main parameters that have been previously discussed, the first that should be discussed is the application type. Apart from being important on its own, it will also be contemplated on the further analysis of the other three parameters, and as such it should come first. This analysis follows the structure that has been proposed in the previous chapter and that is present in the final review matrix, where the articles are classified according to the application models they present. It is divided in two axes of analysis, where both the realism of the data used for the application and the focus of the conclusions taken by each author are considered; this organization can be viewed in Table 5.

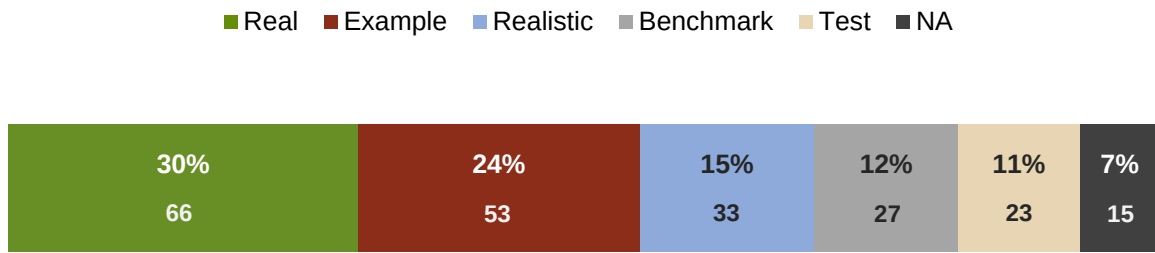


Figure 15 - Selected articles by application type

Figure 15 shows both the count of all articles by their application type (in absolute numbers) and their distribution (in percentage of all articles). It is possible to see that their distribution is more or less balanced, without any of them having a clear majority. Nonetheless, the “real” applications have the most instances of all the analysed papers, with “realistic” applications having half of the latter’s count. Together, they make up 45% of the selected literature, showing that a large number of papers that test their models on real data has been found. On the opposite axis, considering papers that focus on more practical conclusions, it is visible that they make up a majority of the literature, as “real” applications and “examples” form 54% of all articles. There is also a relevant presence of cases that present “benchmark” applications, with most of them applying the model developed by Mandl (1980) (as is visible in the review matrix); these articles are 12% of the selected literature. It is also significant that 7% of the articles present no application, only describing theoretically their proposed optimization model.

Although this classification is somewhat balanced, the difference in size between these categories also influences the results found through the breakdown of the other parameters according to their application type. However, the comparison in scale with this distribution may provide interesting insights on the relationship between the chosen parameters and the focus of each specific study, and whether they are more theoretical or practice oriented.

4.2.3. PROBLEM CATEGORY ANALYSIS

The problem categories were initially defined according to the five steps proposed by Ceder and Wilson (1986). These categories represent the step (or steps) that the authors of each article attempt to solve, as defined in the methodology chapter; as not all authors clearly stated their positioning on this problem, there was a degree of subjectivity in this classification as some interpretation was required. Nonetheless, the results obtained provide a good starting point for this analysis.

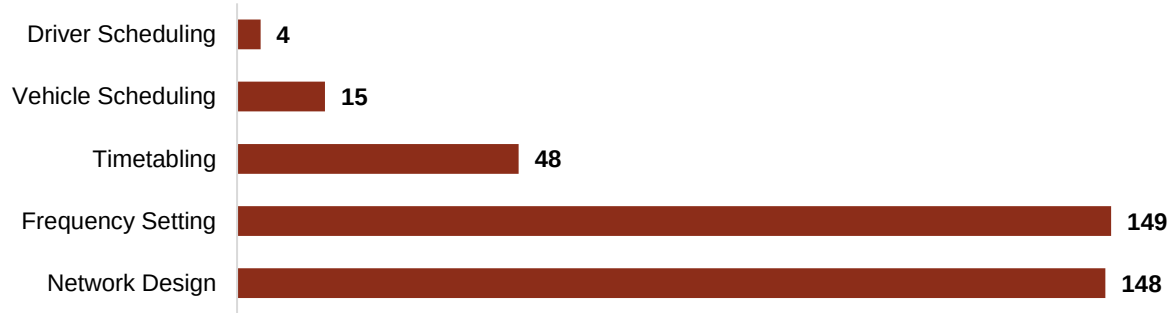


Figure 16 - Selected articles by problem category

Figure 16 represents the number of articles by each problem category, which was obtained by counting them separately (not considering the existing combinations and interactions between categories). The results show that there is an unevenness of the types of problems found in the selected literature, as the network design and frequency setting sub-problems have a clear majority. This may, on one hand, mean that the research on the subject has given more attention to these two sub-problems in comparison to the others, which indicates a potential research gap. On the other hand, this unevenness may result from shortcomings in the collection of articles for this review, as there is a possibility that the methodology followed ignored some articles that may have reduced this imbalance. These differences in scale also affect the analysis of the following parameters, as there is a connection between the problem categories and the formulation of the optimization models; this is particularly evident in the analysis of the decision variables, as they are the parameter that mirrors this classification the most.

This isolated analysis, however, is not sufficient to understand the panorama of all problem types. The literature review has shown that these steps are not rigid and separated, as is visible in Appendix B. In the literature, they appear both alone and combined with each other, as some authors try to solve just one step, but others tackle two or more simultaneously. Therefore, a more in-depth analysis should also consider problem types as groups of sub-problems, ideally to be able to construct problem definitions.

For this end, a model was constructed with all possible combinations of the separate problem categories. This resulted in 31 possible combinations (5 single categories, 10 in pairs, 10 in groups of three, 5 in groups of four, and one with all five combined), and all occurrences of each of these instances was counted to find out what combinations actually exist in the literature. The results of this process are presented in Table 9 (with all possible combinations except the combination of the five categories) and Figure 17 (which shows only the non-zero results).

Table 9 - Results of all possible combinations of problem categories.

ND	34	ND FS	105	ND FS TT	2	ND FS TT VS	1
		ND TT	1	ND FS VS	2		
FS	21	ND VS	2	ND FS DS	0	ND FS TT DS	0
		ND DS	0	ND TT VS	0		
TT	21	FS TT	15	ND TT DS	0	ND FS VS DS	0
		FS VS	1	ND VS DS	0		
VS	1	FS DS	0	FS TT VS	1	ND TT VS DS	0
		TT VS	5	FS TT DS	0		
DS	1	TT DS	1	FS VS DS	0	FS TT VS DS	0
		VS DS	1	TT VS DS	0		

(**ND** – Network Design; **FS** – Frequency Setting; **TT** – Timetabling; **VS** – Vehicle Scheduling; **DS** – Driver Scheduling)

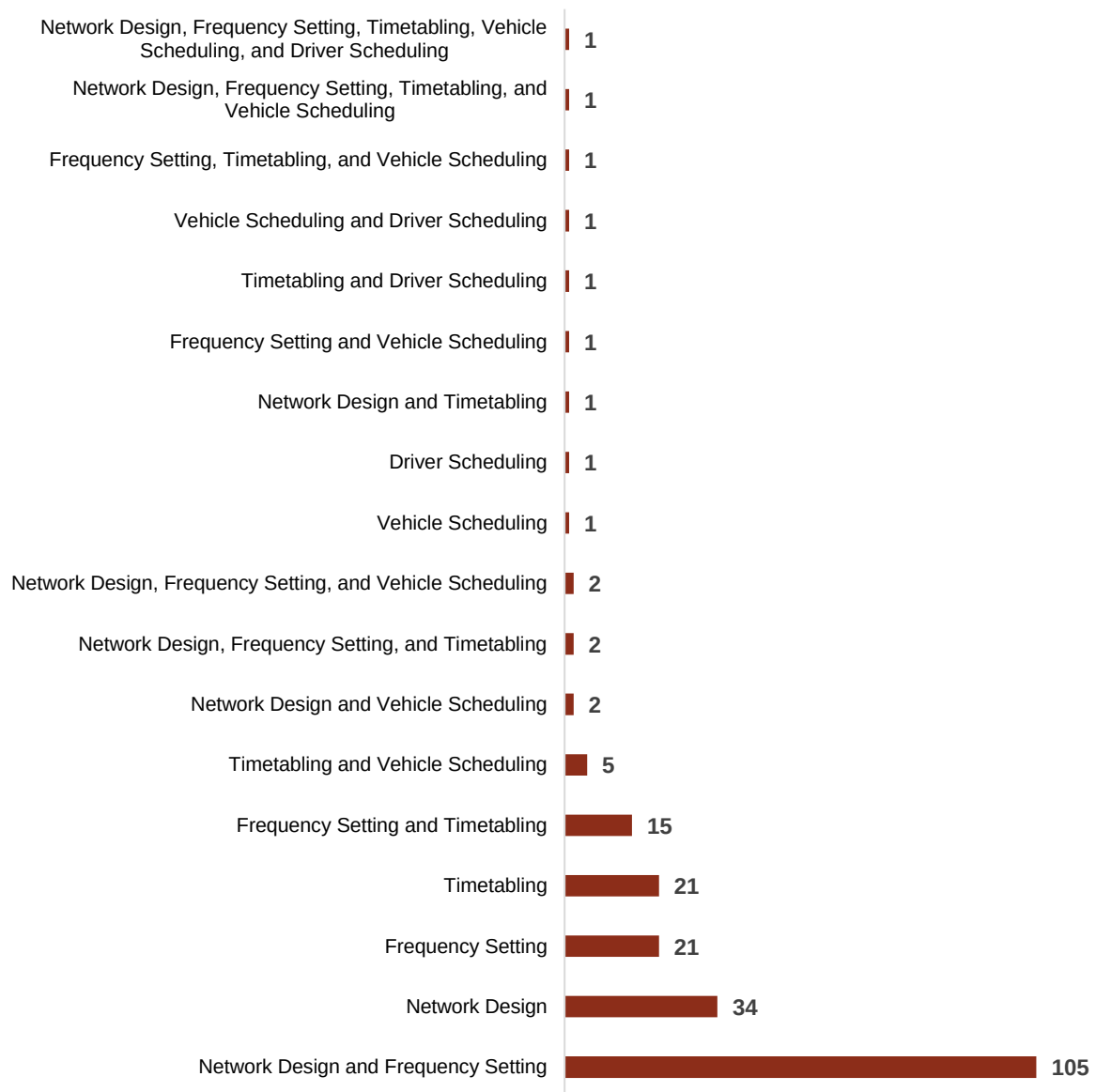


Figure 17 - Problem category combinations (non-zero)

The first observation that can be made is that not all of the combinations have similar results. Many combinations (particularly those that include more than two problems) do not have any instances, while some combinations are more frequent. For example, network design and frequency setting combined have more instances than any of them separated, while vehicle and driver scheduling only appear once isolated. These results confirm that in many cases the combination of problem categories is more significant than the categories themselves, and therefore the analysis is incomplete without these combinations.

An interesting result that is noticeable is the striking resemblance of the most frequent categories to the definitions by Guihaire and Hao (2008) that are shown in Figure 2. The authors considered the first three steps (network design, frequency setting, and timetabling) not only as isolated sub-problems but also the overlap between them, and the pairs that they considered are relatively frequent in Figure 17. The exception is the inclusion of some cases of vehicle scheduling combined with timetabling and network design, which expand upon the scope defined by those authors.

It is also possible to apprehend from this analysis that there are cases of authors that “jump” steps of the traditional process, which challenges the idea that these steps are strictly sequential. While a majority focuses on the first two steps, which are closely intertwined, some authors solve network design and vehicle scheduling problems simultaneously, as well as network design and timetabling or vehicle scheduling and frequency setting. Although these cases are a minority, they show that there may be many possibilities of cross-pollination on the connections between these sub-problems.

In order to perform further analysis (such as comparisons with the other parameters, that will be presented in the end of this chapter), there is a need to further identify and classify these combinations of sub-problems. Many of these combinations, however, only have a single example of their application; although they are interesting on their own, they add complexity to their systematization. For this purpose, it was decided to ignore problem combinations that were not found in more than one instance, in order to give clarity and legibility to further analysis.

The nine most frequent cases are shown in Figure 18, including combinations of categories and isolated cases that appear by exclusion (when they appear alone, without any other problem category). The results are also separated by application type, in order to show the relationship between the “realism” of the model (if the data is real or theoretical and if the conclusions are focused on practical concerns) and the sub-problem considered. In this figure, it is visible that the “benchmark” cases only appear in network design problems and network design and frequency setting problems, which is related to the existing benchmark models in the literature. Also, network design problems and frequency setting problems alone have a majority of “real” and “realistic” applications, while when they are considered together there is a majority of “example” and “test” applications.

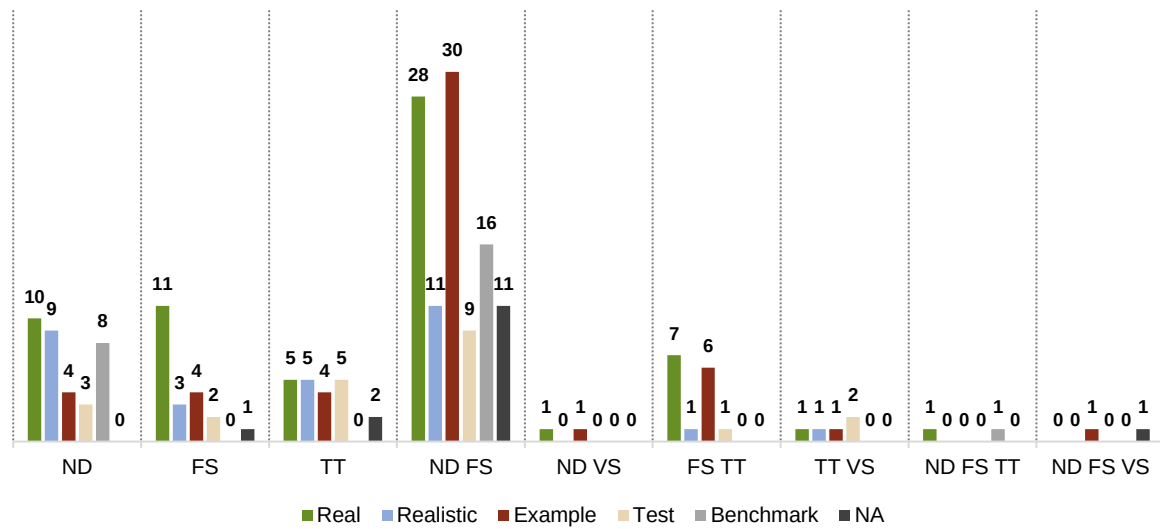


Figure 18 - Problem category combinations by application type

(ND – Network Design; FS – Frequency Setting; TT – Timetabling; VS – Vehicle Scheduling; DS – Driver Scheduling)

4.2.4. OBJECTIVE FUNCTION ANALYSIS

The data presented in Figure 19 is divided in two ways. It considers if the objective function is either for minimization or maximization of a certain parameter, and further divides them by category – if the focus is on the user or on the operator (or other miscellaneous objectives). This division helps the legibility of the data, as it breaks down the identified objectives into similar groups.

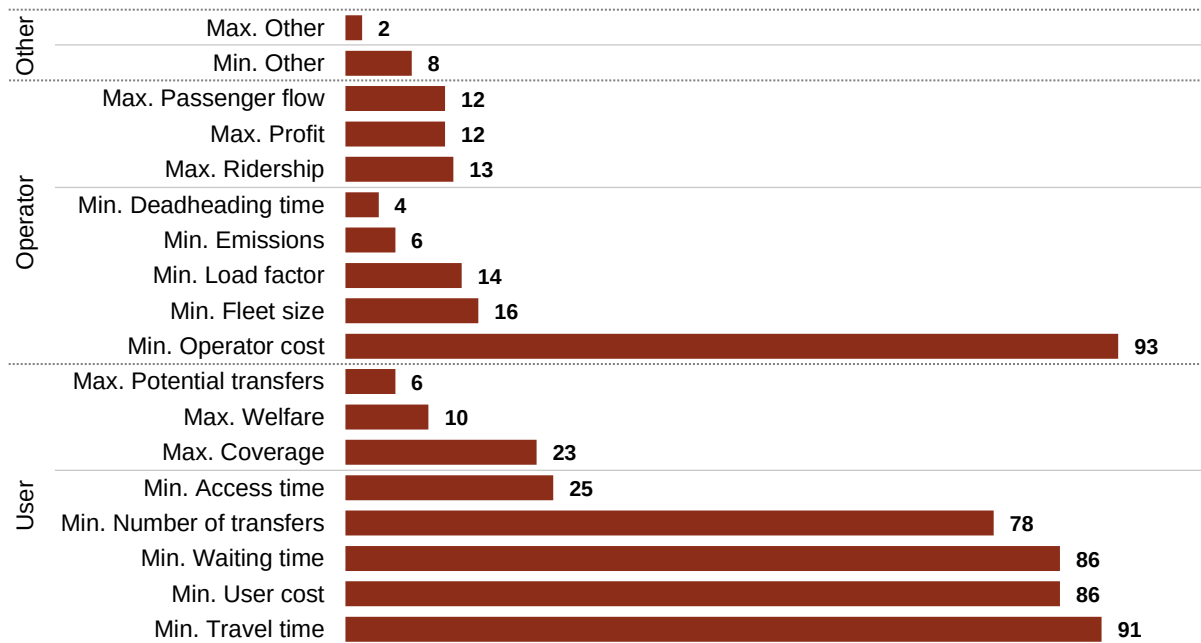


Figure 19 - Selected articles by objective function

This figure shows that more papers adopted minimization objectives than maximization objectives. This conclusion is also tied to the observation that the most common optimization objective is the minimization of operator cost, but there is also a predominance of other minimization objectives focused on the user, such as the minimization of the number of transfers, travel time, waiting time, or overall user cost. In comparison, all the other objectives that have been identified were much more marginal, and it is possible to see in the review matrix that the user and the operator cost minimization objectives appear predominantly together, as many articles aim for a generalized cost minimization objective. It is also interesting to note that, as has been explained in Table 6, the overall travel time minimization objective was separated into three separate phases, including access time, waiting time, and actual in-vehicle travel time. These three categories are shown to be very prevalent in the image, although they appear together often (as is visible in the review matrix); travel time (in-vehicle) is the most frequent, followed by waiting time and then by access time, which is the less prevalent of these subdivisions.

It is also visible that the user-focused objectives appear to be more predominant. Apart from the operator cost minimization objective, most other operator-focused objectives appear to be less frequent than the their counterparts; the numbers are quite balanced for the load factor and fleet size minimization and passenger flow, profit, and ridership maximization objectives, which appear in between 12 to 16 papers.

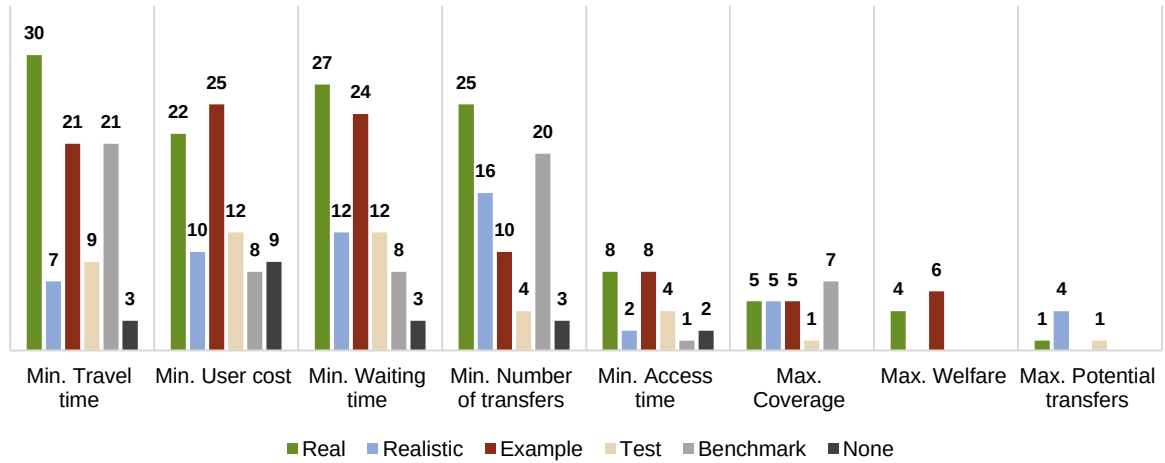


Figure 20 - User focused objectives divided by application type

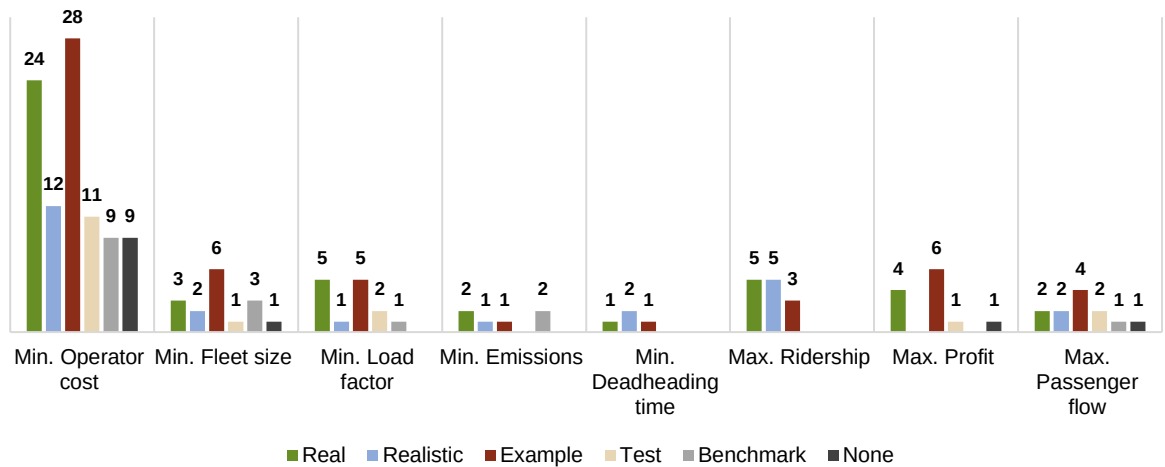


Figure 21 - Operator focused objectives divided by application type

The data shown in Figure 20 and Figure 21 was obtained by breaking down the results of the objective function by application type. The legibility of these results is not immediate, as they are simultaneously influenced by the sample size of both the objective categories and the application types; as some categories have so little instances, the data may not be representative. However, it is still possible to identify some trends on these graphs that may lead to insights on the analysed literature.

The most immediately visible conclusion is that, following what has already been identified in the analysis of the application type alone, the most prominent categories are the real cases and the examples, which still dominate in this particular breakdown. However, there are select cases that stand out, such as the prominence of benchmark applications in papers that minimize travel time and number of transfers, and in those whose objective is to maximize coverage (where the benchmark cases are the majority). In the case of papers that minimize user and/or operator cost (that are very frequently paired), there are more examples than real cases, although these two application types still make up the majority of cases. One particularly interesting case is verified in the articles that state the objective of minimizing fleet size, where real and realistic applications are in the minority.

4.2.5. CONSTRAINTS ANALYSIS

The constraints were organized through a similar method that was applied for the objectives, where they were divided thematically among different categories (as described in 3.3.3.3.). In this case, five categories were identified, as is presented in Figure 13, and the results for each are shown in Figure 22.

This analysis shows that the most frequently appearing constraints are the network structure and the demand matrix, that correspond to the definitions presented in Table 7; this, along with the review matrix itself, indicates that these constraints correspond to the basic inputs for the majority of network design models. Excluding these two, the next most frequent constraints are the vehicle capacity and the fleet size, that correspond to the majority of fleet-related constraints. The category of demand constraints is heavily dominated by the demand matrix constraint, as other forms of demand modelling are much sparser. This is, however, not verified in the case of network constraints, where there is much more diversity and other constraints apart from the network structure appear more often. Budget constraints are less frequent, and the majority is related to unit costs. There were other constraints that did not fit in these four categories and were thus considered separately; many of these, along with others that appear in the four main categories, are marginal, having been identified in a handful of papers.

Figure 23 shows the grouping of each of the previously discussed constraint categories. It presents a similar picture to Figure 22, but shows the differences in scale more clearly. It is more visible that budget constraints are much less frequent than others, as not many papers take actual budgets into consideration; it is interesting to compare this with the prevalence of cost minimization objectives, which shows that these costs are more a measure of the inefficiency of the system than of actual monetary losses by either the user or the operator. It can also be seen that network constraints appear in almost all selected articles (86%), and that there is also a high number of articles with demand constraints. However, the sum of the separate demand constraints (in Figure 22) is the same as the number of overall demand constraints (160), which means that all of them are exclusive, i.e., the classification of demand constraints is never duplicated. This is the opposite of the network constraints, where the sum of all subcategories (293) is larger than the grouped value, which means that they have more overlap.

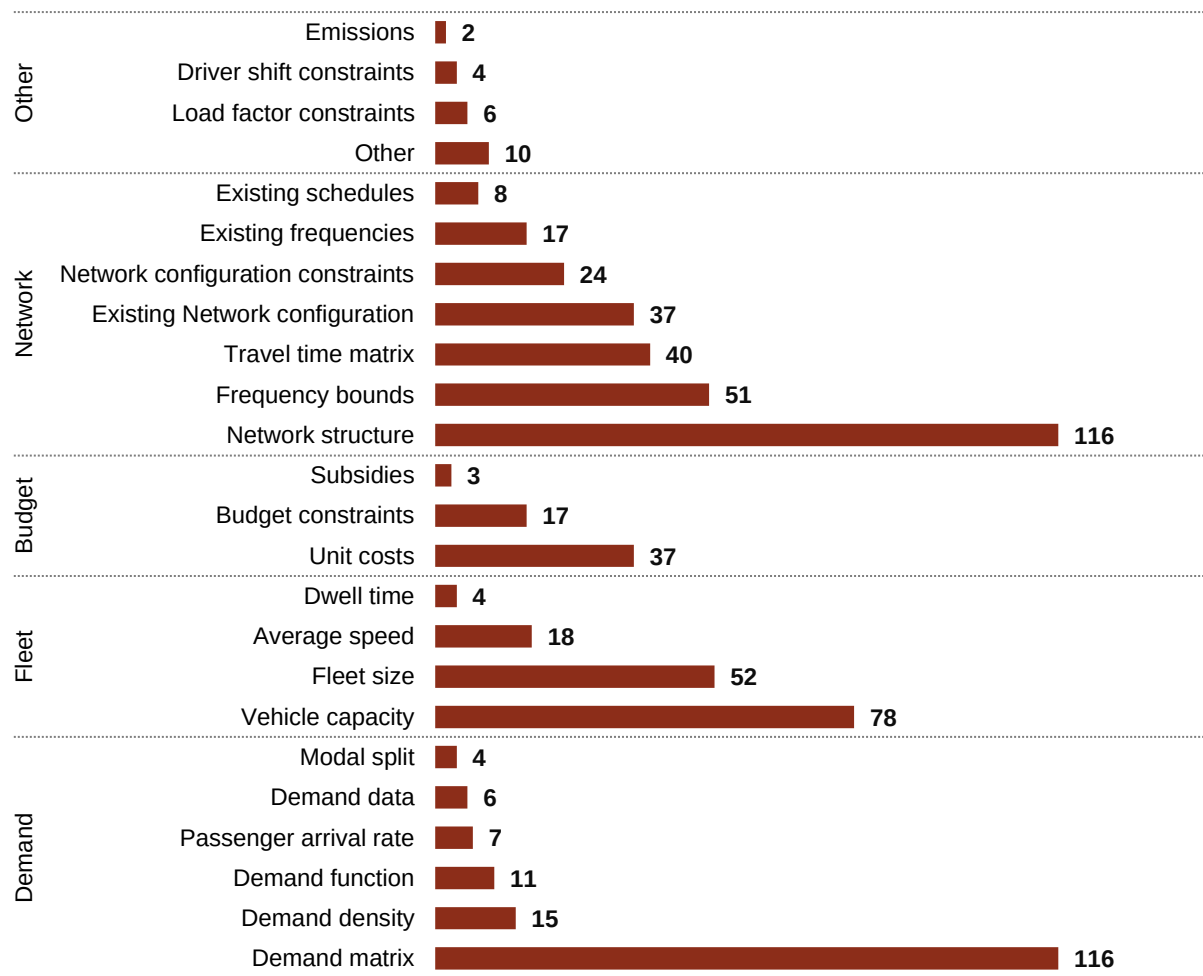


Figure 22 - Selected articles by constraints

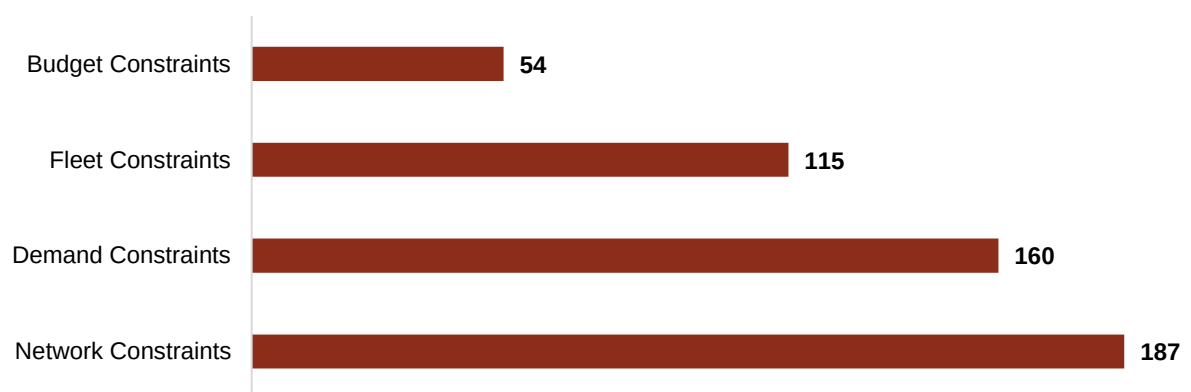


Figure 23 - Selected articles by constraint category

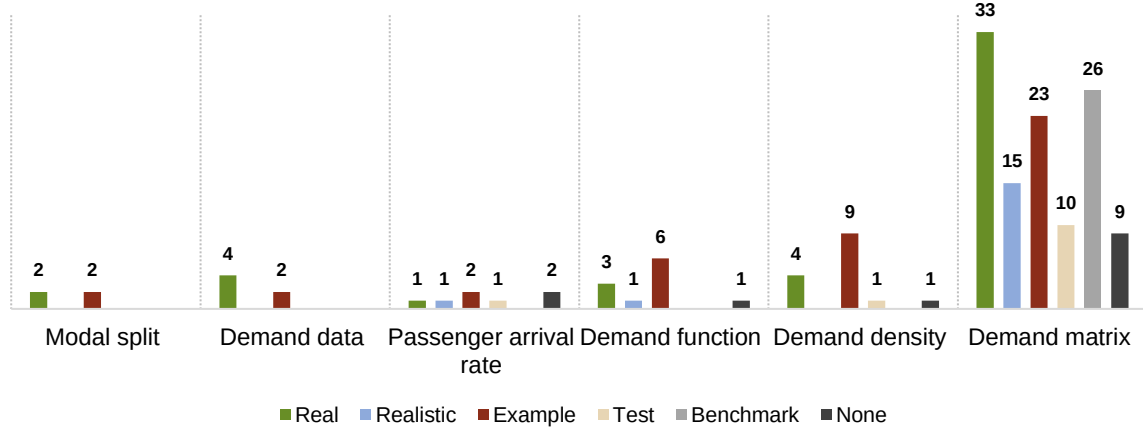


Figure 24 - Demand constraints divided by application type

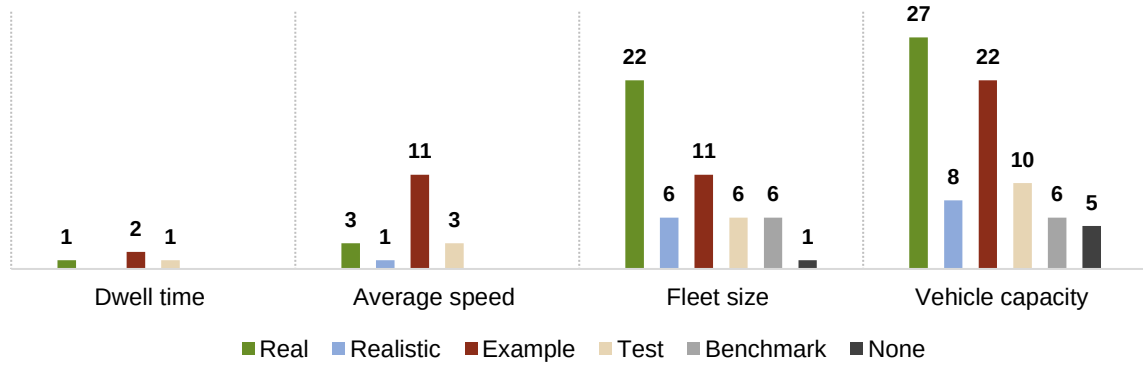


Figure 25 - Fleet constraints divided by application type

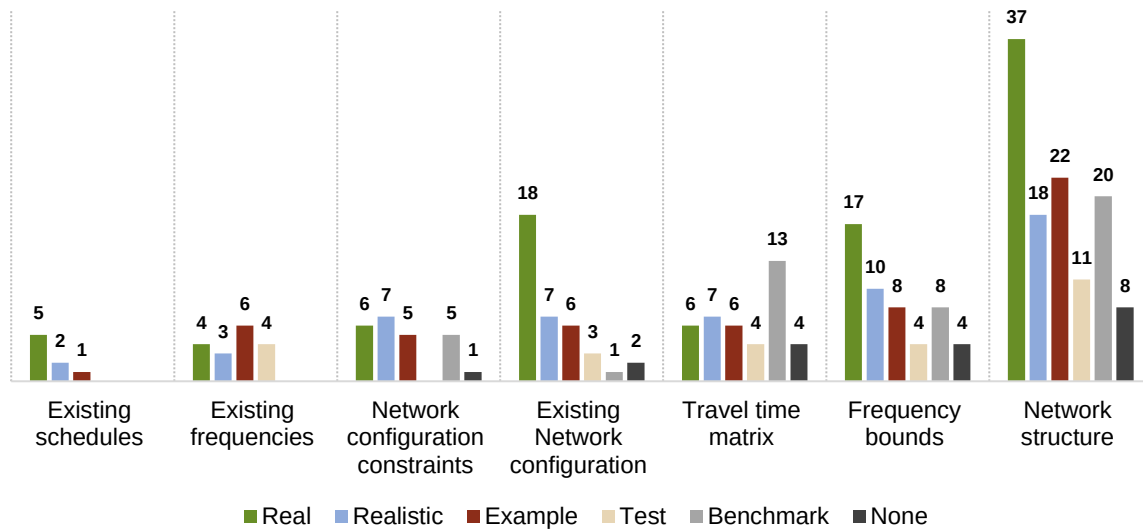


Figure 26 - Network constraints divided by application type

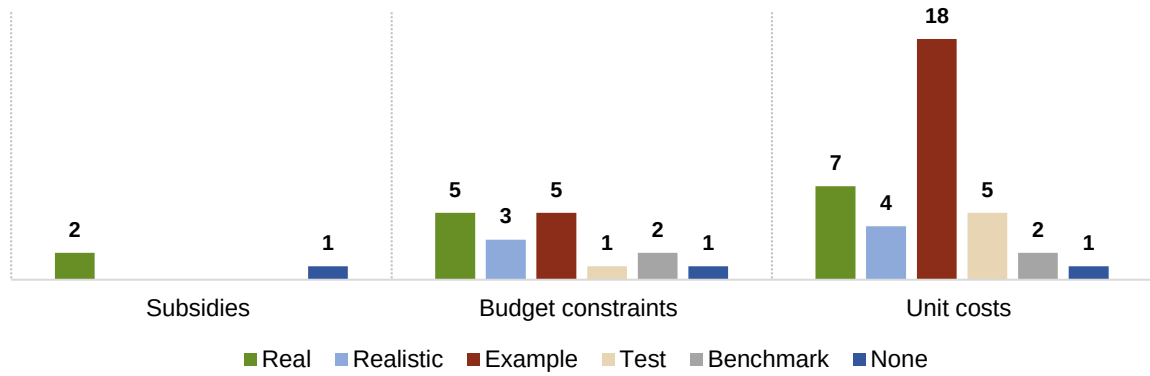


Figure 27 - Budget constraints divided by application type

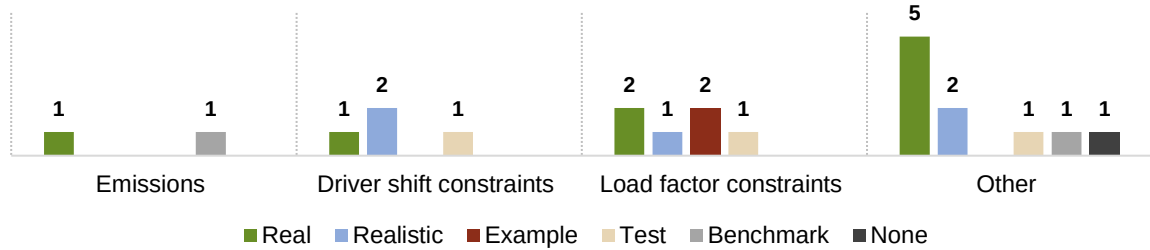


Figure 28 - Other constraints divided by application type

The constraints, like the objectives, were separated by application type. In this case, for graphical reasons, they were divided in five different figures (Figure 24, Figure 25, Figure 26, Figure 27, and Figure 28), with each corresponding to one of the previously established categories. This division was done in order to preserve individual legibility.

It is visible that, for many constraints, the previously identified pattern of the most prominent application types being real cases and examples is the same. However, unlike the objectives, the breakdown of constraints offers more varied results with more interesting exceptions. One of these is that the budget constraints appear to be more prevalent in cases without real data applications; this is also verified in cases with travel time matrix constraints, which have more benchmark applications. The opposite is verified in cases that apply frequency bounds, the existing network configuration, and the fleet size as constraints, where real applications are predominant, indicating that they may be more relevant in practical applications.

4.2.6. DECISION VARIABLES ANALYSIS

The decision variables were also counted according to the categories that were previously defined, and its results are shown in Figure 29. As only 12 main variables (excluding “others”) were determined, it was not so necessary to divide them in groups as was performed for the objectives and constraints, as they would not add much to the legibility of the results. Their variety was not as great as was found in the other parameters, and their definitions (as defined in Table 8) are more clearly divided.

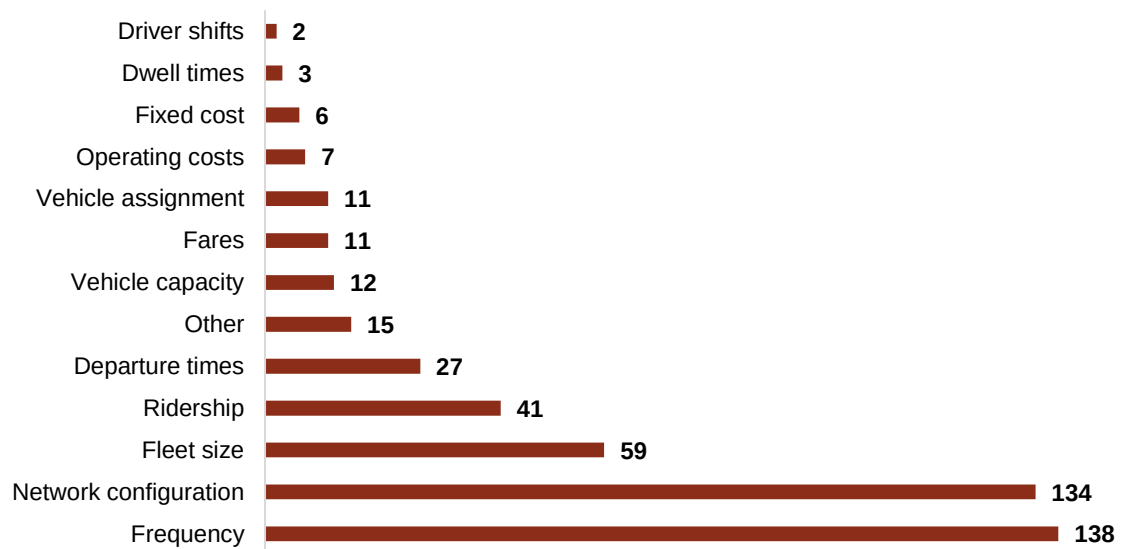


Figure 29 - Selected articles by decision variables

The decision variables are the parameter that more clearly shows the focus of the model proposed by each paper, as they represent the desired results of the optimization model. The most frequent decision variables, network configuration and frequency, correspond directly to the first two steps of the network design problem, as proposed by Ceder and Wilson (1986), and they appear in the majority of articles. A clear comparison can also be made with the results for problem type, as the same pattern is visible in both analyses; a majority of the studies considered tackle these first two steps, and the results for the decision variables corroborate that observation. This may also demonstrate the unevenness of the selected literature, as studies that tackle network design and frequency setting may be overrepresented.

Excluding these two predominant decision variables, fleet size and ridership come next in order of representation in the selected literature; the determination of the required fleet size to operate at a certain service level is also a frequent variable considered in many network design problems, and ridership as a decision variable also appears as a consequence of demand assignment in many problems. The determination of departure times, which is an important variable for timetable development and optimization, appears less frequently, which also may mean that less articles that tackled timetabling problems have been selected. The variables related to driver and vehicle scheduling are also scarce, which may indicate an underrepresentation of these kinds of problems in the literature.

Figure 30 represents the same data but divided by application type, as was presented for the objectives and constraints. The conclusions that may be taken from this data are, as for the previous parameters, influenced by the different samples for each variable, and should not be taken as certain; they are, however, interesting indicators of the relationship between the variables and the applications. One possible reading is that articles that employ the two most frequent variables develop a large number of real and realistic applications, as well as ridership and departure times. Problems that have taken the fleet size, vehicle capacity, vehicle assignment, and fares as decision variables lean more towards examples, as their application cases tend to be less realistic and more theoretical. These conclusions are harder to see for the less frequent variables, as their sample size is smaller and less representative.

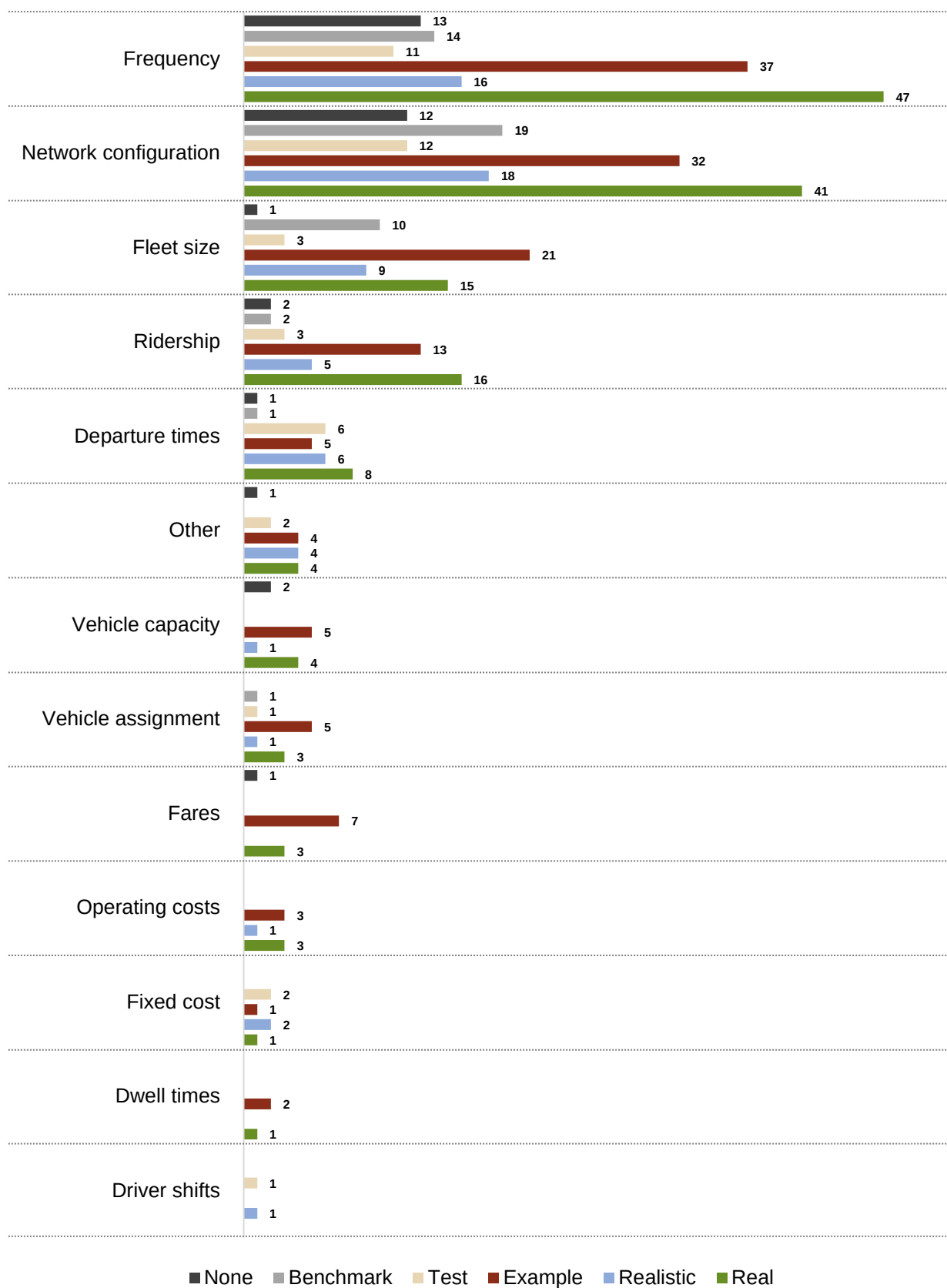


Figure 30 - Decision variables divided by application type

5

CONCLUSIONS

This study presents a literature review on the Bus Network Design Problem from the point of view of approaches and solutions presented in research. Building upon the work of previous authors who have performed similar reviews, this study attempted to bridge some of the gaps that were identified among them, such as the unevenness in selection criteria, included literature, and framework of analysis, as was discussed in Chapter 2. Thus, the main objective was to perform a more comprehensive and updated review of the existing literature, following a clear methodology and performing analysis through a well-defined framework.

The methodology defined and described in Chapter 3 yielded the results that are shown in Appendix A and Appendix B, and was followed by the analysis performed in Chapter 4. The analysis was based on the transformation of the original review matrix into a binary matrix (presented in Appendix B) and consisted of a breakdown of the data according to various criteria. This allowed for a descriptive analysis of the reviewed literature that enabled the observation of common themes and dominant parameters, which were described according to each defined category.

The final results of the literature review contain a large amount of information, and the efforts that were made in the analysis intended to help extract meaning from this data. The system through which this information is presented in both the review matrices and their descriptive analysis follows the framework that was proposed in the definition of the methodology, and clearly presents the observations that were originally intended in the introduction. Therefore, it is possible to conclude that the main objective of this study was met – to review and classify the existing literature on the subject, understanding and analysing its main components and the dominant approaches.

Apart from the stated main objective, there was also a need to define research questions for this study, which were listed in Chapter 1. Nonetheless, the nature of the present work is still fairly open-ended, as it allows for further conclusions that are not limited to the initial research questions. These questions were defined to guide the focus of the work, but they don't contain it; rather, as was stated in the definition of the methodology, the intention was to generate new questions from the observation of the data (or, in this case, the literature). The conclusions of this study, however, will be limited to the initial hypotheses that were considered, while alluding to some other possible questions that may be answered by future studies.

One of the initial hypotheses that were considered was the existence of a dissociation between the focus of the research produced on this topic and the actual needs of professional practice. The analysis of the articles by the classification of their application type demonstrated that, although "real" applications were found to be the most frequent category, they only make up 30% of all considered papers. This reinforces the initial hypothesis, given that the model applications and conclusions of a majority of

studies were theoretical in nature. These findings are also corroborated by the analysis performed according to the other parameters, where the most frequent categories also had a minority of real applications. This does not, however, fully answer the question on its own, as it is limited to the approaches from research; this could require further studies on practical approaches, gathering data and knowledge from real applications to compare with the existing theory.

Another conclusion related to the previous one is the observation of a tendency for some parameters (constraints and decision variables) to appear more frequently in studies oriented towards real cases, and others in more theoretical models. The former may be more aligned with existing practical applications, while the inclusion of the latter may make sense from a theoretical perspective but be inadequate in reality. For example, it was found that the consideration of fleet size as a decision variable appeared more frequently in studies without real applications, as well as considering fares as a variable. Conversely, the consideration of fleet size as a constraint was more frequent in practically oriented studies. Other parameters such as the existing network configuration constraint were also found to be more predominant in studies with real applications.

The question of the positioning of the authors on the balance between the interests of the user and the operator was less clear. The results for the objective function show that there is a balance between user-focused and operator-focused objectives, although there is a greater tendency towards the former. They also appear frequently together, as most articles simultaneously consider the interests of both parties when designing networks, optimising both operator cost/profit and user comfort. However, the applications of many models that considered both objectives – particularly those which generated changes to existing networks – resulted in the reduction of the decision variables (such as line density, frequency, or fleet size) as optimal results, which may hint at a greater weight being placed on the perspective of the rationalisation of operator costs. This is, however, not a straightforward issue, as in some settings this may generate overall social value, while in others it may be detrimental to it. The modelling of user and operator objectives as a balance may yield results that do not benefit society as a whole; it is interesting to note that the optimisation objective of the maximisation of overall social welfare was only found in 10 articles, which constitute a strong minority of those analysed.

The previous consideration also highlights an aspect that was not considered as a criterion for the analysis but may be important for the understanding of existing approaches: the location of the application for the real cases. This was identified in the first review matrix but was not systematically analysed, and may constitute an interesting direction for future studies, as cities of different sizes, with different social conditions and problems, and with different organisations of the transportation market require different focuses for the implementation or improvement of their respective transit networks; it may be relevant to study the impact of these local characteristics in the development of models and methods for transit optimisation.

The main limitations of the present work should also be noted. While the methodology that was defined for the collection of literature was followed carefully, some relevant articles may have been missed during this process. As such, while the final sample is quite extensive, this review may not be fully comprehensive, as further papers that fit the scope of this work may exist that were not included. Another characteristic of this work that may be a limitation is the degree of interpretation that was required for the classification of the selected literature. The activity of summarising each paper into small bits of information for the review matrix required a subjective interpretation of their contents, as well as the construction of the definitions that were necessary for the categorisation. As such, while this approach tried to be as rigorous as possible, some articles may have been misinterpreted. Finally, this work was also limited in its conclusions, as it generated a large amount of information which was not easy to interpret. There may be insights on the literature that were missed due to the limited scope of the analysis performed; however, the results from this work also have the potential to inform future studies on the subject and allow future researchers to extract even more meaning from the gathered data.

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APPENDIX A

N°	YEAR	AUTHOR(S)	TITLE	OBJECTIVES	CONSTRAINTS	DECISION VARIABLES	METHODOLOGY	APP. TYPE	APPLICATION CASE	SAMPLE SIZE	OBSERVATIONS	PRESENT IN:			
												GH	KK	IR	FH
1	1967	Lampkin and Saalmans	The Design of Routes, Service Frequencies, and Schedules for a Municipal Bus Undertaking: A Case Study	Maximize operator profit and service quality	demand distribution (ticket data)	fleet size; frequencies; route configuration	Heuristic	Real	Municipal Bus Company of a small town of North England	16 routes	Skeleton Method	yes	yes	no	yes
2	1971	Newell	Dispatching policies for a transportation route.	Minimize waiting times	fleet size; passenger arrival rate; vehicle capacity;	headways	Analytical	None				no	no	yes	no
3	1971	Rea	Designing urban transit systems: An approach to the route technology selection problem	Multiple possible objectives depending on planner input	demand matrix; network structure	network configuration; headways; vehicle capacity; vehicle technology	Heuristic	Example	Numerical example on template network	16 hypothetical networks (templates)	Incorporates service level and choice of transportation technology in algorithmic procedure	no	yes	no	no
4	1972	Salzborn	Optimum bus scheduling	Minimize fleet size and passenger waiting time	passenger arrival rate; vehicle capacity	fleet size; departure times;	Analytical	Example	Derived from passenger statistics from Adelaide, Australia	single line	Determine optimal schedules and minimal fleet size for a single route or for combination of two routes	yes	yes	yes	no
5	1973	Hurdle	Minimum cost locations for parallel public transit lines.	Minimize user (walking time) and operator cost	passenger arrival rate;	line spacing; frequencies	Analytical	None			Feeder line spacing on a horizontal axis (rapid transit line)	no	yes	no	no
6	1974	Silman et al.	Planning the route system for urban buses	Minimize travel time and crowding	fleet size; demand matrix; vehicle capacity	network configuration; headways;	Heuristic	Test	Haifa Transportation Master-Plan Study	50 zones and 30 routes		yes	yes	no	yes
7	1975	Byrne	Public transportation line positions and headways for minimum user and system cost in a radial case	Minimize user and operator costs	average speed; fleet size; unit costs;	network configuration; headways;	Analytical	Example	Theoretical		Optimal positions for radial lines in a model city with uniform demand	no	yes	no	no
8	1975	Clarens and Hurdle	An operating strategy for a commuter bus system	Minimize user and operator costs	unit costs; passenger arrival rate; travel time matrix; vehicle capacity	Zone size; frequencies	Analytical	Realistic	San Francisco (fictitious density pattern)		Model assumes radial lines from central terminal to suburban pick-up/drop-off "zones"; solves for zone size	no	no	yes	no
9	1976	Byrne	Cost minimizing positions, lengths and headways for parallel public transit lines having different speeds.	Minimize user and operator costs	average speed; population density; unit costs;	network configuration; headways;	Analytical	Example	Theoretical		Optimal positions for parallel lines in a model rectangular city	no	yes	no	no
10	1976	Rapp	Transfer optimisation in an interactive graphic system for transit planning	Minimize transfer time	existing network; fleet size; headways and layover times	average waiting time; departure times; number of transfers	Heuristic	Real	Basel Transit System	82 buses	Interactive graphical system for optimization; transfer optimization	yes	no	no	no
11	1978	Black	Optimizing urban mass transit systems: A general model.	Minimize total costs	network structure; demand matrix; unit costs	network configuration; frequencies; travel time; vehicle assignment	Analytical	Example	Hypothetical circular city, strictly radial network		Route and stop spacing in radial networks, considering costs and transportation technology	no	yes	no	no

N°	YEAR	AUTHOR(S)	TITLE	OBJECTIVES	CONSTRAINTS	DECISION VARIABLES	METHODOLOGY	APP. TYPE	APPLICATION CASE	SAMPLE SIZE	OBSERVATIONS	PRESENT IN:			
												GH	KK	IR	FH
12	1979	Dubois et al.	A Set of Methods in Transportation Network Synthesis and Analysis	Minimize total travel time	network structure; demand matrix; travel time matrix; modal split;	route configuration; headways	Heuristic (Local Search)	Real	10 towns of France (Nice and Toulouse more significant)	95 nodes, 164 links	Method developed and tested with decision-makers in French towns	yes	yes	no	yes
13	1979	Newell	Some Issues Relating to the Optimal Design of Bus Routes	Minimize user and operator cost	demand matrix; vehicle capacity	route spacing; headways;	Analytical	None			Mathematical formulation of the route design problem on rectangular grids	no	no	no	no
14	1980	Mandl	Evaluation and optimisation of urban public transportation networks	Minimize transportation costs (waiting, travel, and transfer time)	network structure; demand matrix; fleet size	network configuration; passenger assignment; vehicle assignment	Heuristic	Test	Belgian town	18 routes, 420 nodes, 1800 arcs	Application used extensively as benchmark afterwards	yes	yes	no	yes
15	1980	Salzborn	Scheduling bus systems with interchanges	Minimize fleet size and passenger waiting time	network configuration; travel time matrix; headways	fleet size; departure times;	Mathematical	Example	Canberra	14 routes	Timetable optimisation for feeder routes	yes	no	no	no
16	1980	Scheele	A supply model for public transit services	Minimize total passenger travel time	network configuration; fleet size; demand matrix; vehicle capacity	frequencies	Non-linear programming	Real	Linköping, Sweden	6 lines, 34 buses		yes	no	yes	no
17	1981	Furth and Wilson	Setting frequencies on bus routes: Theory and practice	Maximize net social benefit	fleet size; subsidies; vehicle capacity; policy headways	headways; ridership; fares; fleet size	Mathematical programming	Real	Boston	21 lines, 70 buses		yes	yes	yes	no
18	1982	Han and Wilson	The allocation of buses in heavily utilized networks with overlapping routes	Minimize waiting times and load factor	fleet size bounds; demand matrix; vehicle capacity	fleet size; ridership; vehicle assignment; frequencies	Heuristic	Example	Cairo	3 lines, 6 nodes	Optimization of frequencies and vehicle assignment in overcrowded and overlapping lines	yes	no	yes	no
19	1982	Kocur and Hendrickson	Design of local bus service with demand equilibrium	Maximization of operator profitability and user benefit	demand function; budget constraints; vehicle capacity	route spacing; headways; fare; ridership	Analytical	Example	Numerical (derived from Hartford, CT)			no	yes	no	no
20	1983	Tsao and Schonfeld	Optimization of zonal transit service.	Minimize total cost	demand matrix; vehicle speed; number of zones	Zone size; frequencies	Analytical	Real	Washington DC metropolitan area	1 bus corridor	Zonal transit service in a radial structure (trips to/from CBD)	no	yes	no	no
21	1984	Ceder	Bus frequency determination using passenger count data.	Minimize fleet size and number of bus runs	demand matrix (from data collection); network configuration; vehicle capacity; policy headways	frequencies; fleet size; ridership; departure times	Heuristic	Real	Jerusalem	Passenger count data from single line	Enhance frequencies and timetables with passenger data collection	no	no	yes	no
22	1984	Marwah et al.	Optimal design of bus routes and frequencies for Ahmedabad.	Minimize operating and passenger time cost	network structure; fleet size; demand matrix	frequencies; network configuration; transfers	Heuristic	Real	Ahmedabad, India	426 arcs, 134 nodes	Generation of new routes from existing bus network	no	yes	yes	no
23	1984	Morlok and Vinton	Feasibility of profitable transit service in radial urban corridors	Maximize profitability	vehicle capacity; demand matrix (peak hours); unit costs;	network configuration (number of routes, length); frequencies; fares; modal split; fleet size	Analytical	Example	San Francisco (income and demand data)		Obtain capacity, service quality and price that maximizes profit	no	yes	no	no

N°	YEAR	AUTHOR(S)	TITLE	OBJECTIVES	CONSTRAINTS	DECISION VARIABLES	METHODOLOGY	APP. TYPE	APPLICATION CASE	SAMPLE SIZE	OBSERVATIONS	PRESENT IN:			
												GH	KK	IR	FH
24	1986	Ceder and Wilson	Bus network design	Minimize user (travel and waiting time) and operator cost (vehicle)	network structure (nodes, terminals); demand matrix; travel time matrix; frequency bounds; max. fleet size; unit costs	network configuration (length); frequencies; fleet size; waiting times; excess travel time	Heuristic	Example	Simple five node network	5 nodes	Seminal paper for the definition of the steps involved in network planning - notes rarity of integral system redesigns	yes	yes	yes	yes
25	1986	Vaughan	Optimum polar networks for an urban bus system with a many-to-many travel demand	Minimize travel time	fleet size; vehicle speed; network structure; population	route spacing; headways; walking time; travel time	Analytical	Example	Model radial city; data from Perth, Australia		Theoretical relation between city shape and route spacing and headways using an abstract model	no	yes	no	no
26	1987	Klemm and Stemme	Schedule synchronization for public transit networks	Minimize transfer cost	network configuration; frequencies;	departure times; waiting times	Heuristic, enumeration	Test				yes	no	yes	no
27	1987	Van Oudheusden et al	The design of bus route systems—An interactive location allocation approach	Multiple possible objectives through cost minimization	network structure; demand matrix; initial route set; frequencies	network configuration; cost (multiple objective)	Mathematical programming (SCP, SPLP)	Example	Fictional city	41 "zones"	Interactive model for line planning - allows planner to choose optimization objective and decision variables	no	yes	no	no
28	1988	Leblanc	Transit system network design	Maximize transit usage and minimize operator cost	demand matrix; demand assignment; headway bounds	modal split; frequencies	Hooke-Jeeves algorithm	Realistic	Data from Sioux Falls, USA	128 links (5 added lines)		no	yes	no	no
29	1988	Van Nes et al.	Design of public transport networks	Maximize number of passengers, minimize transfers	network structure; budget constraints; max. fleet size; demand matrix	network configuration; fleet size; frequencies	Heuristic	Real	Groningen, Netherlands	115 zones, 182 nodes	Single step method - argues that routes and frequencies cannot be solved separately	yes	yes	yes	yes
30	1989	Domschke	Schedule synchronization for public transit systems.	Minimize waiting times	network configuration; headways; demand matrix; time matrix	departure times; waiting times	Heuristic, branch and bound algorithm	Test	Numerical test to evaluate fitness of algorithm	14 routes		no	no	yes	no
31	1991	Baaj and Mahmassani	An AI-based approach for transit route system planning and design	Minimize number of transfers and total travel time	network structure; demand matrix; initial route set	headways; route configuration; transfers; fleet size; travel time	Hybrid (Artificial Intelligence-AI)	Benchmark	Mandl's Benchmark Network (Swiss network)			no	yes	yes	no
32	1991	Chang and Schonfeld	Multiple period optimization of bus transit systems.	Maximize social welfare and operator profit	demand function; unit costs; vehicle capacity	route spacing; headways; fleet size; fares	Analytical	Example	Numerical example		Feeder line spacing in multiple variable demand scenarios	no	yes	no	no
33	1992	Bookbinder and Désilets	Transfer optimization in a transit network	Minimize waiting times	network configuration; headways; disutility function	waiting times; offset times	Integer programming	Test	Two examples: one fictional, one with data from Winnipeg		Transfer optimization with fixed headways and random travel time	yes	no	yes	no
34	1993	Chang and Schonfeld	Welfare maximization with financial constraints for bus transit systems	Maximize welfare	budget constraints (subsidies); demand function; unit costs; vehicle capacity	network configuration; headways; fares; fleet size	Analytical	Example	Numerical analysis		Maximization of overall welfare and consumer surplus considering subsidy constraints and elastic demand	no	yes	no	no

N°	YEAR	AUTHOR(S)	TITLE	OBJECTIVES	CONSTRAINTS	DECISION VARIABLES	METHODOLOGY	APP. TYPE	APPLICATION CASE	SAMPLE SIZE	OBSERVATIONS	PRESENT IN:			
												GH	KK	IR	FH
35	1993	Chang and Schonfeld	Optimal dimensions of bus service zones	Minimize cost (user and operator)	demand density; unit costs; average speed;	zone size; network configuration (route spacing and length); headways	Analytical	Example	Numerical analysis		Zonal service (local/express mixed lines)	no	yes	no	no
36	1993	Spasovic and Schonfeld	Method for optimizing transit service coverage	Minimize total cost (user and operator)	average speed; unit costs; vehicle capacity	network configuration (route length and spacing); headways; fleet size	Analytical	Example	Numerical analysis		Zonal service (local/express mixed lines)	no	yes	no	no
37	1994	Spasovic et al.	Bus transit service coverage for maximum profit and social welfare	Maximize profit and social welfare	demand function; budget constraint; network structure (corridor size)	route length; route spacing; frequencies; fares; fleet size	Analytical	Example	Sensitivity analysis	Single corridor	Correlation between operator profit and social welfare	no	yes	no	no
38	1995	Baaj and Mahmassani	Hybrid route generation heuristic algorithm for the design of transit networks	Minimize user and operator costs	network structure; headway bounds; demand matrix; vehicle capacity	demand satisfaction; fleet size; network configuration	Heuristic	Test	Sensitivity analysis			yes	no	yes	yes
39	1995	Chakroborty et al.	Optimal scheduling of urban transit systems using genetic algorithms	Minimize waiting and transfer times	policy headways; stopping time bounds; fleet size	headways; stopping times; departure times	Genetic algorithm	Example	Numerical example	3 routes, 30 vehicles	Transfer optimization	yes	no	yes	no
40	1995	Constantin and Florian	Optimizing frequencies in a transit network: A nonlinear bi-level programming approach	Minimize waiting time	network configuration; fleet size; vehicle capacity; headway bounds	waiting times; frequencies; demand assignment	Nonlinear Bi-level Programming	Real	Stockholm, Winnipeg, Portland			yes	yes	yes	no
41	1995	Daduna and Voss	Practical experiences in schedule synchronization	Minimize waiting times	network configuration; frequencies; travel times	departure times; waiting time	Tabu search method	Realistic	Cities from Germany (unspecified)	14 routes	Transfer optimization subject to multiple side constraints - objective is interactive optimization for planners	yes	no	yes	no
42	1997	Chien and Schonfeld	Optimization of grid transit system in heterogeneous urban environment	Minimize user, operator, and capital costs	demand matrix; zone size	total travel time; route spacing; headways	Analytical	Test	Sensitivity analysis		Focus on spatial characteristics: heterogeneous urban areas	no	yes	yes	no
43	1998	Bielli et al.	A New Approach for Transport Network Design and Optimization	Multicriteria analysis - multiple possible optimization objectives	demand matrix; subsidies; fleet size policy headways	network configuration; headways	Genetic algorithm	None			Algorithm theory - no optimization objectives or application example	no	yes	no	no
44	1998	Ceder and Israeli	User and Operator Perspectives in Transit Network Design	Minimize user (travel and waiting time) and operator costs (fleet size)	network structure; demand matrix; travel time matrix; length bounds	network configuration; frequencies; waiting times; passenger hours; fleet size	Heuristic	None				no	yes	no	no
45	1998	Imam	Optimal design of public bus service with demand equilibrium	Maximize operator profit	vehicle capacity; demand function; unit costs;	route spacing; headways; fares; zone size	Analytical	None			Takes demand into account - variable demand with service level	no	yes	no	no
46	1998	Pattnaik et al.	Urban Bus Transit Route Network Design Using Genetic Algorithm	Minimize user and operator cost	network structure; demand matrix; route length bounds	fleet size; network configuration; number of transfers; frequencies	Genetic algorithm	Realistic	Madras, India	25 nodes, 39 links		yes	yes	no	yes

N°	YEAR	AUTHOR(S)	TITLE	OBJECTIVES	CONSTRAINTS	DECISION VARIABLES	METHODOLOGY	APP. TYPE	APPLICATION CASE	SAMPLE SIZE	OBSERVATIONS	PRESENT IN:			
												GH	KK	IR	FH
47	1998	Shih et al.	Planning and design model for transit route networks with coordinated operations	Minimize user cost (waiting time and number of transfers) and operator cost (fleet size and operating costs)	network structure; demand matrix; service level bounds	network configuration; frequencies; vehicle capacity; fleet size; number of transfers; fuel consumption	AI search heuristic	Realistic	Austin transit network	177 nodes, 40 lines	Variable vehicle sizes, demand-responsive transit; solutions to highly suburbanized areas (US)	yes	yes	no	yes
48	2000	Soehodho and Nahry	Optimal scheduling of public transport fleet at network fleet	Minimize waiting time, fleet size	network configuration; headways; vehicle capacity	waiting time; fleet size; departure times; vehicle assignment	Dynamic programming algorithm	Test	Numerical	3 routes, 4 terminals, 5 stops	Operational level optimization - algorithm to enhance timetables and vehicle rostering simultaneously	no	yes	no	no
49	2000	Furth and Rahbee	Dynamic Programming and Geographic Modelling	Minimize walking time, delay cost and operator cost	demand distribution (modelling); network structure;	stop spacing; walking time;	Dynamic programming algorithm	Real	Boston, USA	Single line	Bus stop spacing adjustment	no	no	yes	no
50	2001	Ceder et al.	Creating bus timetables with maximal synchronization	Maximize simultaneous bus arrivals in transfer points	network configuration; headway bounds; travel times	departure times; frequencies	Heuristic	Real	Examples and real case from Israel	14 lines and 3 nodes		yes	no	yes	no
51	2001	Chakroborty et al.	Optimal fleet size distribution and scheduling of urban transit systems using genetic algorithms	Minimize total waiting time	total fleet size; stopping time bounds; policy headways;	headways; stopping time; vehicle assignment	Genetic algorithm	Example		3 routes, 30 buses		yes	no	no	no
52	2001	Chien et al.	Genetic Algorithm approach for transit route planning and design	Minimize total cost (operator and user)	network structure; vehicle capacity; budget constraints; zone size	headways; network configuration; travel time; walking time	Genetic algorithm	Test	Numerical analysis of model area		Evolutionary Process Method	no	yes	no	no
53	2001	De Palma and Lindsey	Optimal timetables for public transportation	Minimize schedule delay costs	demand assignment; network configuration	departure times	Analytical	None			Optimization based on idealized models	yes	no	yes	no
54	2001	Delle site and Fillippi	Bus service optimization with fuel saving objective and various financial constraints	Minimize fuel consumption	demand assignment; budget constraints	fares; vehicle capacity	Analytical	Example	Numerical, database derived from peak hour conditions in Rome		Consideration of modal split between bus and car and impact on total fuel consumption	no	yes	no	no
55	2002	Bielli et al.	Genetic algorithms in bus network optimization	Multicriteria analysis - multiple possible optimization objectives	network structure; vehicle capacity; demand matrix	fleet size; ridership; network configuration; transfers; travel time; emissions; headways	Genetic algorithm	Realistic	Parma, Italy		Optimization based on fitness function and multiple performance indicators	yes	yes	no	yes
56	2002	Ceder	Designing Public Transport Network and Routes.	Minimize travel times (in passenger-hours) and fleet size	network structure; demand matrix; travel time matrix; policy headway	fleet size; travel time and waiting time savings; empty space-hours	Mixed integer linear programming	Example	8 node example network		[NOTE Fig. 1] Both route design and operational optimization methods are considered	yes	no	yes	yes
57	2002	Chakroborty and Wivedi	Optimal Route Network Design for Transit Systems Using Genetic Algorithms	Minimize travel time and transfers	road network; demand matrix;	travel time; number of transfers; demand satisfaction;	Genetic algorithm	Benchmark	Mandl's benchmark network			yes	yes	yes	yes

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58	2002	Chien and Spasovic	Optimization of grid bus transit systems with elastic demand	Maximize operator profit and total social welfare	network structure; demand density; vehicle capacity; unit costs; average speed	route spacing; length; frequency; fares	Analytical	Example	Fictional simplified grid			no	no	yes	no
59	2002	Chowdhury and Chien	Intermodal Transit System Coordination	Minimize operator costs and user costs for both modes (bus and rail)	network configuration; existing frequencies; demand matrix; vehicle capacity	headways; operating costs; waiting times	Heuristic	Example	Numerical examples		Multimodal integration of main lines and feeder routes	yes	no	no	no
60	2002	El-Hifnawi, M.	Cross-town bus routes as a solution for decentralized travel: a cost-benefit analysis for Monterrey, Mexico	Maximize total welfare (operator cost, minimizing bus user and car user total travel time)	travel time matrix; modal split; existing network configuration; demand assignment	number of transfers; travel time; operating cost	Analytical	Real	Monterrey, Mexico	114 existing lines, 16 new cross-town lines	Simulation and evaluation of net welfare benefits following introduction of new lines to an established system	no	no	no	no
61	2002	Fusco et al.	A heuristic transit network design algorithm for medium size towns	Minimize overall system costs	network structure; demand matrix; travel time matrix;	route configuration; headways; demand satisfaction	Genetic algorithm	None	Mand'l's benchmark network		Incomplete application of proposed model (benchmark)	yes	no	no	yes
62	2002	Shrivastava and Dhingra	Development of coordinated schedules using Genetic Algorithms.	Minimize transfer times	existing schedules; network configuration; demand assignment; vehicle capacity	load factor; transfer times; headways	Genetic algorithm	Real	Optimization on a single railway station (Andheri, India)		Multimodal optimization: railway and bus interface	no	no	yes	no
63	2002	Shrivastava et al.	Application of Genetic Algorithm for scheduling and schedule coordination problems.	Minimize waiting times, operation cost, unsatisfied demand	existing schedules; network configuration; vehicle capacity	frequency; departure times; transfers; travel time; fleet size	Genetic algorithm	Real	Andheri and Vileparle suburban stations (India); comparison with benchmark results			no	no	yes	no
64	2002	Yan and Chen	A scheduling model and a solution algorithm for intercity bus carriers	Maximize profit	demand matrix; fleet size bounds; network configuration; vehicle capacity	fleet size; demand satisfaction; transfers	Heuristic	Real	Taiwan intercity bus network (5 cities)	320 buses, 15120 nodes, 85680 arcs		yes	no	no	no
65	2003	Ceder	Public Transport Timetabling and Vehicle Scheduling.	Minimize user and operator costs	demand data; vehicle capacity; policy headways	fleet size; headways; departure times	Heuristic	Example			Graphical method for determining frequencies and timetables with operator cost reduction objective (reducing fleet size)	yes	no	no	no
66	2003	Chakroborty	Genetic algorithms for optimal urban transit network design	Maximize demand satisfaction, minimize total travel time and number of transfers	road network; demand matrix; travel time matrix; fleet size; policy headways	number of transfers; average travel time; demand satisfaction	Genetic algorithm	Benchmark	Mand'l's benchmark network		Main goal is to make an argument for the application of genetic algorithms	no	yes	yes	no
67	2003	Chien et al.	Optimization of bus route planning in urban commuter networks	Minimize total system costs	network structure; vehicle capacity; demand density; unit costs	network configuration; headways; fleet size; total travel time	Analytical	Example	Model grid (similar to US cities with grid pattern and diagonal thoroughfares)		Approximation of irregular grid networks to perfect grids for model application	no	yes	no	no

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68	2003	Murray	A coverage model for improving public transit system accessibility and expanding access	Maximize transit coverage, minimize required bus stops	network structure (zones, stops);	network configuration (bus stop location); service coverage	Hybrid algorithm	Real	Brisbane, Australia	685 stops	Determine location of new transit stops to maximize accessibility	yes	no	no	no
69	2003	Ngamchai and Lovell	Optimal time transfer in bus transit route network design using a genetic algorithm	Minimize total system costs	demand matrix; network structure; unit costs; vehicle capacity; average speed	network configuration; headways	Genetic algorithm	Test	Network adapted from Pattnaik et al. (1998)			yes	yes	no	yes
70	2003	Quak	Bus line planning.	Minimize operator cost, minimize detour time (compared to driving time)	network structure; demand matrix; travel time matrix; unit costs	frequencies; departure times; network configuration; travel time; vehicle capacity	Greedy heuristic	Real	Amersfoort, Netherlands	125 bus stops	Modelling of passenger costs through mean estimated detour time and operating costs through total drive time	yes	no	no	no
71	2003	Tom and Mohan	Transit route network design using frequency coded genetic algorithm	Minimize total system costs	network structure; demand matrix; travel time matrix; frequency bounds; unit costs	network configuration (routes, length); transfers; fleet size; frequencies	Genetic algorithm	Realistic	Chennai, India	Medium sized network (75 nodes and 125 links)		yes	yes	no	yes
72	2003	Van Nes	Multuser-Class Urban Transit Network Design	Maximize social welfare	network structure; demand density; demand sensitivity;	network configuration (line and stop spacing); total travel time; frequency	Conventional (analytical)	Example	Urban bus corridor of Utrecht, Netherlands	Single corridor		no	yes	no	no
73	2003	Wan and Lo	A mixed integer formulation for multiple-route transit network design.	Maximum coverage (demand satisfying) at minimum cost	network structure; demand matrix; vehicle capacity	network configuration (route length); frequencies	Mixed integer programming	Example	Example network	10 nodes, 19 arcs		yes	no	yes	yes
74	2003	Zhao and Gan	Optimization of Transit Network to minimize Transfers	Minimize number of transfers, maximize service coverage	network structure (set); network configuration;	network configuration; transfers;	Heuristic/metaheuristic (SA, tabu Search, NS)	Realistic	Transit System of Miami-Dade County, Florida	2804 nodes, 81 bus lines	Software developed for interactive line planning with possibility of using existing network or policy requirements as constraints	yes	yes	no	yes
75	2004	Agrawal and Mathew	Transit route design using parallel genetic algorithm	Minimize total system cost	frequency bounds; load factor constraints; vehicle capacity; network structure; demand matrix	network configuration; frequencies; transfers; fleet size	Genetic algorithm	Realistic	Delhi, India	1,332 nodes and 4,076 links		no	yes	yes	yes
76	2004	Aldaihani et al.	Network design for a grid hybrid transit service	Optimize number of zones	zone size; passenger arrival rate; unit costs	number of zones; travel times; dead-heading times; fleet size; waiting times; vehicle assignment	Analytical	Example			Development of a grid zone structure for integration of demand-responsive and fixed schedule transit services	no	no	no	no
77	2004	Carresse and Gorri	An urban bus network design procedure	Minimize travel times, waiting times, operator cost	network structure (existing railway network); demand matrix; fleet size bounds; vehicle capacity	network configuration; passenger flows (ridership); headways; fleet size; demand assignment	Heuristic	Real	Rome, Italy	Application to a large city, 1400 nodes and 7700 links		yes	yes	no	yes

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78	2004	Castelli <i>et al.</i>	Scheduling multimodal transportation systems.	Minimize operator costs and passenger holding costs	demand matrix (fixed, incoming and outgoing); network configuration; travel time matrix; unit costs	departure times; demand assignment; headways	Heuristic	Test			Scheduling based on transfer optimization applied line by line	yes	no	yes	no
79	2004	Chakroborty	Optimal Routing and Scheduling in Transportation: Using Genetic Algorithm to Solve Difficult Optimization Problems	Various performance indicators	demand matrix; fleet size; vehicle capacity; policy headways;	demand satisfaction; number of transfers; average travel time, man-hours saved; departure times	Genetic algorithm	Benchmark	Mandl's network (benchmark)		Solves route design, time-tabling and vehicle routing from depot in separate steps	no	no	no	no
80	2004	Cipriani <i>et al.</i>	A procedure for the solution of the urban bus network design problem with elastic demand	Minimize overall system costs	demand matrix (variable); network structure	network configuration; frequencies; vehicle capacity	Genetic algorithm	None				no	yes	no	no
81	2004	Eranksi	A model to create bus timetables to attain maximum synchronization considering waiting times at transfer stops.	Minimize waiting times, maximize simultaneous arrivals	existing network configuration; frequencies	waiting times	Heuristic	Realistic	Real data derived from Ceder <i>et al.</i> (2001)		Simultaneous arrival defined as a time window	yes	no	no	no
82	2004	Fan and Machemehl	Optimal Transit Route Network Design Problem: Algorithms, Implementations, and Numerical Results	Minimize total travel time and fleet size	demand matrix; network structure; headway bounds; network configuration constraints; load factor bounds	network configuration (route length, number of lines); headway; load factor; fleet size; travel time (waiting, in-vehicle, and walking)	Hybrid heuristics (Variety of NS algorithms)	Example	Various numerical examples			yes	no	yes	yes
83	2004	Fleurent <i>et al.</i>	Transit timetable synchronization: evaluation and optimization	Minimize waiting times	existing network configuration; frequencies	waiting times	Heuristic	Real	Montréal, Canada		"Meet" builder software: timetable synchronization for simultaneous arrivals	yes	no	no	no
84	2004	Gao <i>et al.</i>	A continuous equilibrium network design model and algorithm for transit systems	Minimize user and operator cost	demand matrix; network structure (set); demand assignment	network configuration; frequencies; passenger flows	Heuristic (Sensitivity analysis)	Example	Numerical example			yes	no	yes	no
85	2004	Petrelli	A transit network design model for urban areas	Minimize user and operator costs	demand matrix; network structure; frequency bounds	network configuration; vehicle capacity; frequency; transfers	Genetic algorithm	None	Application to a model network and a medium-sized city (not included in paper)			no	yes	no	no
86	2004	Wong and Leung	Timetable synchronization for mass transit railway	Minimize waiting times	existing network configuration; frequencies	waiting times	Heuristic	Real	Hong Kong Mass Transit Railway network		Railway timetable synchronization	yes	no	no	no
87	2004	Zhao and Ubaka	Transit network optimization – minimizing transfers and optimizing route directness	Minimize transfers, optimize service coverage	demand matrix; network structure;	number of transfers; route length; number of routes	Greedy search method, Fast hill climbing search method	Benchmark	Mandl's benchmark network, Miami-Dade County network			yes	no	no	yes

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88	2005	Bachelet and Yon	Enhancing theoretical optimization solutions by coupling with simulation.	Minimize travel times and route length	network structure; route length bounds; demand matrix	route length; travel times	Heuristic	Realistic	Clermont-Ferrand, France	109 nodes, 392 arcs	Simulation optimization approach to design networks and evaluate solutions	yes	no	no	no
89	2005	Borndorfer <i>et al.</i>	A path-based model for line planning in public transport	Minimize operating costs and travel times	demand matrix	fixed and variable costs; passenger travel times	Heuristic	Test	Potsdam, Germany	80 lines	Multi-commodity flow model for line planning	yes	no	no	no
90	2005	Hu <i>et al.</i>	Optimal design for urban mass transit network based on evolutionary algorithms	Minimize user and operator costs	vehicle capacity; route length bounds; network structure (terminals); demand matrix	network configuration (route length, stops); headways	Genetic algorithm, Ant colony algorithm	Real	RD: Changchun, China FS: Hong Kong	20 routes		no	yes	no	yes
91	2005	Jansen <i>et al.</i>	Minimizing passenger transfer times in public transport timetables	Minimize weighted sum of transfer waiting times	existing network; fixed frequencies	perceived cost (amount passengers are willing to pay for saved transfer time)	Tabu search (heuristic)	Realistic	Copenhagen-Ringsted model (Nelsen <i>et al.</i> 2001)		Transfer optimization based on perceived time savings expressed by cost and for three passenger groups (business, commuters and recreational)	yes	no	no	no
92	2005	Lee and Vuchic	Transit network design with variable demand.	Minimize travel time and social cost, maximize operator profit	network structure; total demand matrix; modal split	network configuration; demand assignment; waiting time; travel time; frequency	Heuristic	Example	Example network	16 nodes	Incorporation of variable demand in iterative network development algorithm	yes	yes	no	yes
93	2005	Lee and Vuchic	Transit network design with variable demand.	Minimize travel time and social cost, maximize operator profit	network structure; total demand matrix; modal split	network configuration; demand assignment; waiting time; travel time; frequency	Heuristic	Example	Example network	16 nodes	Incorporation of variable demand in iterative network development algorithm	yes	yes	no	yes
94	2005	Park	Bus network scheduling with genetic algorithms and simulation	Minimize total cost, minimize transfer times	network configuration and OD matrix	Total cost (divided in multiple components)	Genetic algorithm (deterministic arrival times), simulation-based genetic algorithm (stochastic arrival times)	Example			Different models and analysis for deterministic arrival times and stochastic arrival times	yes	no	no	no
95	2005	Yu <i>et al.</i>	Optimizing bus transit network with parallel ant colony algorithm.	Minimize transfers, maximize passenger flow	network structure; zonal demand matrix; network configuration constraints (route length; stop spacing)	network configuration; passenger flows	Parallel ant colony algorithm	Realistic	Dalian, China	61 lines	Priority of route design over frequency setting	yes	no	no	yes
96	2005	Zhao <i>et al.</i>	Transit network optimization: Minimizing transfers and maximizing service coverage with an integrated simulated annealing and tabu search method	Minimize transfers, maximize service coverage	network structure; demand matrix; fleet size bounds	network configuration; transfers; fleet size; headways	Multiple (heuristic)	Realistic	Miami-Dade County, Florida, USA			no	yes	no	no
97	2006	Cevallos and Zhao	Minimizing transfer times in a public transit network with a genetic algorithm	Optimize transfer times	network configuration; existing timetables;	departure times; time shifting	Genetic algorithm	Real	Broward County Transit, Florida			yes	no	no	no

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					demand data; headways										
98	2006	Fan and Machemehl	Optimal transit route network design problem with variable transit demand: A genetic algorithm approach	Minimize operator cost, user cost and unsatisfied demand	Max/min routes and headways; OD matrix; bus capacity	Number of routes; route length; travel times; fleet size	Genetic algorithm	Example	Experimental network	160 nodes, 418 arcs	Two papers using different methods on same test network; SA achieved better results	yes	yes	yes	yes
99	2006	Fan and Machemehl	Using a simulated annealing algorithm to solve the transit route network design problem	Minimize operator cost, user cost and unsatisfied demand	Max/min routes and headways; OD matrix; bus capacity	Number of routes; route length; travel times; fleet size	Simulated annealing algorithm	Example	Experimental network	160 nodes, 418 arcs	Two papers using different methods on same test network; SA achieved better results	yes	yes	yes	yes
100	2006	Guan et al.	Simultaneous optimization of transit line configuration and passenger line assignment	Minimize travel time and number of transfers	network structure; demand matrix; link capacity; route length bounds	network configuration (route length); travel time; transfers	Analytical	Real	Hong Kong Mass Transit Railway network	6 lines, 49 stations (simplified 9 node network for example)	Linear Binary Integer program	yes	no	yes	yes
101	2006	Matisziw et al.	Strategic route extension in transit networks	Maximize potential demand, minimize route length extension	network configuration; network structure; demand matrix; max. number of new stops	network configuration; demand coverage (binary)	Analytical	Real	Columbus, Ohio bus network	10 stops extension	Focus on strategic extension of pre-existing bus routes	no	no	no	no
102	2006	Schröder and Solchenbach	Optimization of Transfer Quality in Regional Public Transit. Technical	Optimize transfers based on an assessment of their quality (penalties for too early or too late transfers)	transfer classification; network structure; existing timetables	departure times; waiting times	Analytical	Real	Western Palatinate transit association; case studies from Kaiserslautern	240 connections (max)	Improve transfer quality between different operators in regional transit networks	no	no	yes	no
103	2006	Yu and Yang	Model and algorithm for iterative design of bus network	Maximize direct traveller density	network structure; demand matrix; length bounds; vehicle capacity	line length; direct passengers; demand assignment	Ant colony optimisation	Real	Dalian, China	81 lines, 1220 bus stops	Simultaneous optimization of bus network and transit assignment	no	yes	no	no
104	2006	Zhao	Large-scale transit network optimization by minimizing user cost and transfers	Minimize transit transfers and total user cost while maximizing service coverage	demand matrix	travel time; number of transfers; fleet size	Simulated annealing	Benchmark	Mandl's benchmark network, Miami-Dade County network			yes	no	no	yes
105	2006	Zhao and Zeng	Simulated annealing-genetic algorithm for transit network optimization	Minimize transfers, maximize service coverage	network structure; demand matrix; fleet size; route length constraints	network configuration (length, number of routes); transfers	Heuristic / metaheuristic (GA and SA)	Realistic	Miami-Dade County, Florida		Combination of different methods to generate routes with demand coverage criteria based on number of transfers	yes	yes	no	yes
106	2007	Barra et al.	Solving the transit network design problem with constraint programming	No objective function: adequate level of service to demand assignment	demand matrix; demand assignment; budget constraints; network structure; headway bounds	network configuration; ridership; headways	Constraint Programming	None	Attempts to test the model on real networks led to high computational times		Consideration of multiple constraints to be applied to the model depending on their classification	yes	no	no	yes

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107	2007	Liu <i>et al.</i>	Regional bus timetabling model with synchronization. Journal	Minimize transfer times	network structure; high and low departure time intervals; frequency	Synchronization coefficient (calculated from constraints)	Nesting taboo search	Example	Numerical	8 bus routes, 3 connecting hubs	Timetable synchronization for regional bus networks	no	no	yes	no
108	2007	Yang <i>et al.</i>	A parallel ant colony algorithm for bus network optimization	Maximize direct passenger density	Route length limitation	direct passenger density (passengers/route length)	Ant colony optimisation	Realistic	Dalian, China	2300 nodes, 3200 links, 89 routes, 1500 bus stops		no	yes	yes	yes
109	2007	Zhao and Zeng	Optimization of user and operator cost for large scale transit networks	Minimize total cost (operator cost and user travel time)	transit demand; network structure; feasibility constraints	route configuration and number; fleet size; number of transfers	Multiple (heuristic)	Benchmark	Benchmark networks		Focus on large-scale network optimization	no	yes	no	yes
110	2008	Borndorfer <i>et al.</i>	Models for line planning in public transport.	Minimize total passenger travel time and operation costs	demand matrix; network structure; travel time matrix; vehicle capacity; frequency bounds	network configuration; frequencies	Analytical (Integer programming)	None				no	no	no	yes
111	2008	Fan and Machemehl	Tabu search strategies for the public transportation network optimizations with variable transit demand	Minimize the sum of operator cost, user cost and unsatisfied demand costs	demand matrix (variable); fleet size and capacity; network specifications (routes and nodes)	network configuration (length); travel times; demand assignment; load factors; fleet size; frequencies	Tabu search algorithm	Example	Experimental network	28 zones, 160 nodes, 418 arcs		no	no	yes	yes
112	2008	Fernández <i>et al.</i>	Demand responsive urban public transport system design: Methodology and application	Minimize total cost (operator cost and user travel time), maximize social welfare	demand matrix; network structure; fleet size; vehicle capacity	network configuration (route directness); frequencies	Mathematical and Heuristic	Real	Santiago de Chile	370 bus services; demand data obtained from census survey of 15000 households	Metropolitan-scale analysis and modelling of an entire transit network	no	no	yes	no
113	2008	Kwan and Chang	Timetable synchronization of mass rapid transit system using multiobjective evolutionary approach.	Minimize total passenger dissatisfaction index	existing headways and schedules	total passenger dissatisfaction index (measures quality of train connections - not too close and not too far apart)	Genetic algorithm	Realistic	Metro rail system adapted from section of Singapore MRT		Railway timetable synchronization	no	no	yes	no
114	2008	Marin and Jaramillo	Urban rapid transit network capacity expansion	Maximize coverage (upper level), minimize passenger costs and expansion costs (lower level)	network structure; budget constraints; demand matrix	network configuration; construction costs	Heuristic	Realistic	Section of Seville transit network	72 demands (nodes), 4 lines	Capacity expansion of existing lines	no	no	no	no
115	2008	Wong <i>et al.</i>	Optimizing timetable synchronization for rail mass transit.	Minimize transfer times	network configuration; network structure; vehicle capacity; dwell time bounds; headways bounds	departure times; dwell times; waiting times; headways; vehicle assignment	Heuristic (mixed-integer-programming)	Real	Hong Kong Mass Transit Railway network	6 lines, 14 interchange stations		no	no	yes	no

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116	2008	Zhao and Zeng	Optimization of transit route network, vehicle headways, and timetables for large-scale transit networks	Minimize user cost function	network structure; demand matrix; fleet size	network configuration (number and length); headways; load factor	Metaheuristic	Benchmark	Benchmark networks			no	no	yes	no
117	2009	Matta and Peters	Developing work schedules for an inter-city transit system with multiple driver types and fleet types	Minimize total cost of work schedules	network data; number and type of drivers; fleet size and type	driver work scheduling cost	Analytical	Test				no	no	no	no
118	2009	Mauttone and Urquhart	A route set construction algorithm for the transit network design problem	Maximize demand coverage, minimize user cost (travel time) and operator cost (route number and length)	network structure; demand matrix	network configuration (route length and number); travel time; frequencies	Pair Insertion algorithm (PIA)	Real	Rivera, Uruguay	13 lines	Comparison between Route Generation Algorithm (Baaj and Mahmasani, 1995) and the author's own algorithm	no	no	yes	yes
119	2009	Mohaymany and Amiripour	Creating bus timetables under stochastic demand.	Minimize expected waiting times	demand function (stochastic); network configuration; max. fleet size	demand assignment; headways; waiting time; fleet size	Simulation	Example	Sample network	11 bus routes		no	no	yes	no
120	2009	Pacheco et al.	A tabu search approach to an urban transport problem in northern Spain	Minimizing waiting time and travel time	fleet size; drivers' work shifts; demand matrix; travel time matrix; network structure	network configuration; wait times; travel times; vehicle assignment	Heuristic (Local Search and Tabu search)	Real	Burgos, Spain	382 stops, 24 lines, 36 buses		no	no	no	yes
121	2010	Daganzo	Structure of competitive transit networks	Minimize user and operator cost	demand matrix; route length; vehicle capacity	number of transfers; average travel time; zone size; headways	Analytical	None			Explores relationship between network type (radial, grid, hub and spoke) and system cost and performance	no	no	yes	no
122	2010	Fan and Mumford	A metaheuristic approach to the urban transit routing problem.	Minimize total travel time and number of transfers	demand matrix; travel time matrix; network structure	network configuration (number of routes); number of transfers; average travel time	Metaheuristic	Benchmark	Mandl's benchmark network	50 nodes and 65 links		no	no	no	yes
123	2010	Guihaire and Hao	Transit network timetabling and vehicle assignment for regulating authorities	Maximize quality and quantity of transfer opportunities, minimize fleet size and dead-heading trip length	network configuration; initial timetable;	trip starting times; vehicle assignment; fleet size	Iterated Local Search algorithm	Realistic	Data from Loiret area (France) with 3 medium-sized cities	50 lines, 673 stops	Simultaneous solution to timetabling and vehicle assignment problems	no	no	yes	no
124	2010	Guihaire and Hao	Improving timetable quality in scheduled transit networks.	Maximize quality and quantity of transfer opportunities	maximal shift; driver trip assignment; vehicle trip assignment	departure times	Tabu search	Realistic	Data from Loiret area (France) with 3 medium-sized cities	50 lines, 673 stops	Opposite approach: construct timetables from driver and vehicle assignment	no	no	yes	no
125	2010	Lownes and Machemehl	Exact and heuristic methods for public transit circulator design.	Minimize total cost (user, operator, unserved demand)	network structure; demand density; frequency bounds	network configuration; headways	Mixed integer method	Test			Circulator line design - local feeder routes for commuter train stations	no	no	yes	no

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126	2010	Yoo <i>et al.</i>	Frequency design in urban transit networks with variable demand: model and algorithm.	Maximize total demand	fleet size; frequency bounds; demand function; network configuration; vehicle capacity	passenger flow; frequency; waiting time	Gradient projection	Example			Bi-level algorithm - relationship between frequency (level of service) and passenger demand	no	no	yes	no
127	2010	Yu <i>et al.</i>	Genetic algorithm for bus frequency optimization	Minimize travel times	fleet size; demand matrix; vehicle capacity; network configuration	frequency; travel time; waiting time	Genetic algorithm	Realistic	Dalian, China	89 bus lines and 3004 bus stops	Bi-level algorithm - relationship between frequency (level of service) and passenger demand	no	no	yes	no
128	2011	Bagloee and Ceder	Transit-network design methodology for actual-size road networks	Minimize passenger discomfort (generalized time savings)	network structure; demand matrix (fixed); budget constraints; vehicle capacity	network configuration; frequencies; travel time savings; transfers; fleet size	Genetic algorithm	Real	Mandl's benchmark network; Winnipeg, Canada (1976 data); Chicago rail network (2010 data)			no	no	yes	no
129	2011	Curtin and Biba	The transit route arc-node service maximization problem.	Maximize service value	budget constraints (distance); network structure	network configuration (number of routes); service value	Integer linear programming	Realistic	Richardson, Texas (USA)		Cost as constraint and not as minimization objective	no	no	no	yes
130	2011	Estrada <i>et al.</i>	Design and implementation of efficient transit networks: procedure, case study and validity test.	Minimize agency costs (capital costs, operating costs) and user cost (time)	passenger arrival rate; vehicle capacity; network structure; unit costs; policy headways	zone size; line spacing; route length; headways	Analytical	Real	Barcelona	11 lines	High performance bus transit network implementation - use of idealized grid network as guide to real plan development	no	no	yes	no
131	2011	Fan and Machemehl	Bi-level optimization model for public transportation network redesign problem	Minimize total cost (operator, user, and unsatisfied demand cost), travel time and number of transfers	network constraints and requirements; fleet size and capacity; costs	network configuration (length and number of routes); demand assignment; travel times; headways; load factor	Genetic algorithm	Example	Sample network	28 zones, 93 nodes, 284 arcs		no	no	yes	no
132	2011	Szeto and Wu	A simultaneous bus route design and frequency setting problem for Tin Shui Wai, Hong Kong	Minimize transfers and total travel times	network structure; fleet size bounds; frequency bounds; demand matrix	route configuration; frequencies; transfers; average travel time	Genetic algorithm	Real	Tin Shui Wai, Hong Kong	23 stops, 7 terminals	Model devised from the solution of a real case	no	no	no	no
133	2011	Wirasinghe and Van-debona	Route layout analysis for express buses	Minimizing operating cost, passenger accessibility costs (waiting time, travel time)	network structure (passenger generator locations); demand matrix; average speed; unit costs	network configuration; travel time; waiting time;	Analytical	Example	Regular grid network		Demand modelled through passenger generators	no	no	no	no
134	2012	Cipriani <i>et al.</i>	Transit network design: A procedure and an application to a large urban area	Minimize total cost and resources	demand allocation; vehicle capacity; network structure; frequency bounds; load factor bounds	network configuration (route length); frequencies; load factor	Genetic algorithm	Real	Rome, Italy	1300 nodes, 7000 arcs	Consideration of a whole multimodal transit network (rapid rail system, bus, and tram lines)	no	no	yes	yes
135	2012	dell'Olio <i>et al.</i>	Optimizing bus-size and headway in transit networks	Optimize the system's social costs (sum of user and operator costs)	network configuration; fleet size; headway bounds	frequency; bus capacity	Analytical (bi-level)	Real	Santander	19 lines	Bus size and frequency optimization	no	no	yes	no

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												GH	KK	IR	FH
136	2012	Hadas and Shnaiderman	Public-transit frequency setting using minimum-cost approach with stochastic demand and travel time.	Maximize demand fulfilment (min empty seats) and service level	demand (both stochastic and deterministic)	headways; vehicle capacity	Analytical	Example	Numerical example		Frequency optimization for demand fulfilment objective; also considers bus capacity optimization	no	no	yes	no
137	2012	Hassold and Ceder	Multiobjective approach to creating bus timetables with multiple vehicle types	Minimize waiting times, optimize vehicle occupancy	bus capacity; demand	headways; load factor	Heuristic	Real	Auckland, New Zealand		Timetable optimization considering multiple vehicle types (different capacities) and balanced departure times	no	no	yes	no
138	2012	Ibarra-Rojas and Rios-Solis	Synchronization of bus timetabling	Maximize number of synchronizations	headway bounds; network configuration	departure times; line synchronizations; headways	Iterated local search	Realistic	Monterrey, Mexico	300 bus lines	Inter-urban transit line design and integration with urban lines	no	no	yes	no
139	2012	Liebchen and Stiller	Delay resistant timetabling	Maximize punctuality (minimize expected waiting delay)	network structure; travel time	buffer times budget	Heuristic	None			Timetable optimization based on minimization of expected delays through application of buffer times	no	no	yes	no
140	2012	Roca-Riu <i>et al.</i>	The design of interurban bus networks in city centres	Minimize user and operator costs	demand matrix; network configuration; travel times for each arc	route configuration; travel and waiting times; fleet size	Tabu search	Real	Barcelona, Spain	37 lines, 200 demand zones	Inter-urban transit line design and integration with urban lines	no	no	yes	no
141	2012	Sivakumaran <i>et al.</i>	Cost-savings properties of schedule coordination in a simple trunk-and-feeder transit system.	Minimize user cost (waiting and transfer times) and operator cost	vehicle speed; operating and user costs; zone dimensions	feeder line headways; network configuration (route spacing)	Analytical	Example	Example network with single trunk and feeder lines		Feeder and trunk line network for commuter lines with a many-to-one demand structure (single CBD)	no	no	yes	no
142	2012	Song <i>et al.</i>	Research on a Scientific Approach for Bus and Metro Networks Integration	Maximize number of public transport users	demand matrix; demand assignment; network structure	travel times; number of transfers; network configuration (degree of line overlap); bus coverage; revenue	Analytical	Real	Daxing Line, Beijing, China		Integration of bus lines with a newly built metro line	no	no	no	no
143	2012	Szeto and Jiang	Hybrid artificial bee colony algorithm for transit network design	Minimize total travel times and number of transfers	fleet size; demand matrix; network configuration constraints; frequency requirements; network structure; average speed	frequencies; number of transfers; network configuration; waiting time	Hybrid Enhanced Artificial Bee Colony algorithm (HEABC)	Real	Suburban area of Tin Shui Wai, Hong Kong			no	no	yes	no
144	2012	Tilahun and Ong	Bus timetabling as a fuzzy multi-objective optimization problem using preference-based genetic algorithm	Minimize waiting times (multiple objectives)	routes and possible transfer points	initial departure times; waiting times	Genetic algorithm	Test	Example network	10 lines	Optimization of transfers on rural low-frequency (one bus per day) regional bus network	no	no	yes	no

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145	2012	Tribby and Zandbergen	High-resolution spatio-temporal modelling of public transit accessibility	Maximize accessibility (minimize total travel times)	demand density (census population and land use data)	Walking time; waiting time; in-vehicle travel time; network configuration	Analytical	Real	Albuquerque, New Mexico		Application on new BRT lines; prioritizes accessibility by taking travel time as well as spatial GIS data about population	no	no	no	no
146	2012	Yu et al.	Transit route network design-maximizing direct and transfer demand density	Maximize travel density	network structure; demand density; vehicle size	network configuration (route length); transfers; frequencies	Ant colony optimisation	Real	Dalian, China		Results prioritize express routes over feeder routes, minimizing travel times and transfers	no	no	yes	no
147	2013	Ceder et al.	Approaching even-load and even-headway transit timetables using different bus sizes	Minimize load discrepancy and headway unevenness	fleet size; vehicle capacity; bus loading data (demand)	time discrepancy (headway unevenness) and load discrepancy (variation of load factor)	Heuristic	Real	Auckland, New Zealand		Balance between even frequencies (operational inefficiency and crowding) and even load (less friendly for passengers)	no	no	yes	no
148	2013	Chew et al.	Genetic algorithm for bi-objective urban transit routing problem	Minimize user and operator costs	network structure; demand matrix; travel time matrix	average travel time; transfers; network configuration (route length, number of routes)	Genetic algorithm	Benchmark	Mandl's benchmark network			no	no	yes	no
149	2013	Huang et al.	Optimizing bus frequencies under uncertain demand: case study of the transit network in a developing city.	Minimize user and operator costs and travel time variance	fleet size; network configuration	travel times; frequencies	Genetic algorithm	Real	Liupanshui, China	16 lines	Application to a small city in China (uncongested)	no	no	yes	no
150	2013	Jiang et al.	Transit Network Design: A Hybrid Enhanced Artificial Bee Colony Approach and a Case Study	Minimize total travel times and number of transfers	fleet size; demand matrix; network structure; network configuration constraints; policy headways	frequencies; number of transfers; network configuration	Hybrid Enhanced Artificial Bee Colony algorithm (HEABC)	Real	Suburban area of Tin Shui Wai, Hong Kong		Same as Szeto and Jiang (2012) with revisions	no	no	no	no
151	2013	Kermanshahi et al.	Application of a new rapid transit network design model to bus rapid transit network design: Case study Isfahan Metropolitan Area	Maximize daily trip coverage index (meet a predetermined target travel time)	network configuration; demand matrix; budget	coverage; construction costs; travel time; network configuration	Analytical	Real	Isfahan, Iran	56 new lines	Algorithm to develop a set of new BRT routes or optimize extensions to pre-existing ones given a fixed budget	no	no	no	no
152	2013	Kuo	Design method using hybrid of line-type and circular-type routes for transit network system optimization	Minimize passenger travel time and number of transfers	network structure; travel time matrix; OD matrix; operator specifications (number of lines; max route length)	network configuration (route length); number of transfers	Simulated annealing	Benchmark	Mandl's benchmark network and comparison with results from previous authors			no	no	no	no
153	2013	Li et al.	Expected value model for optimizing the multiple bus headways	Maximize operator profit, minimize passenger waiting time cost	vehicle capacity; passenger arrival rate; network structure; unit costs	headways; waiting time	Hybrid intelligent algorithm (SS and GA)	Test	Numerical experiment and comparison with previous authors		Optimize frequencies with stochastic passenger arrival times and travel times	no	no	yes	no

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154	2013	Medina <i>et al.</i>	Model for the optimal location of bus stops and its application to a public transport corridor in Santiago, Chile	Minimize user, operator, and capital costs	demand data (continuous); unit costs; network structure	network configuration (density of stops); headways	Analytical	Real	Grecia Avenue public transport corridor, Santiago, Chile	1 line, 22 stops	Realistic modelling with multiple cost and vehicle specification parameters	no	no	yes	no
155	2013	Mesa <i>et al.</i>	Locating optimal timetables and vehicle schedules in a transit line	Minimize user inconvenience costs	fleet size and capacity; travel and stopping times; vehicle trip assignment	inconvenience cost; demand coverage	Clustering algorithm	Test	Numerical test			no	no	yes	no
156	2013	Nikolic and Teodorovic	Transit network design by bee colony optimization	Minimize number of transfers and total travel time	travel time matrix; demand matrix; network structure	number of transfers; demand satisfaction; average travel time; network configuration	Artificial bee colony algorithm	Benchmark	Mandl's benchmark network and comparison with results from previous authors			no	no	yes	no
157	2013	Sun <i>et al.</i>	Joint optimization of a rail transit route and bus routes in a transit corridor	Maximize rail ridership and minimize total travel time	network configuration	rail ridership; total travel times (waiting; in-vehicle; transfer); network configuration (route node sequence)	Genetic algorithm	Example	Numerical example (model network)		Multimodal transit system (Railway and bus transport)	no	no	no	no
158	2013	Verbas and Mahmassani	Optimal allocation of service frequencies over transit network routes and time periods: formulation, solution and implementation using bus route patterns	Maximize ridership and waiting time savings, minimize net cost	fleet size and capacity; policy headways; budget constraints	headways; waiting time savings; ridership	Nonlinear optimization (KNITRO)	Example	Two model lines			no	no	yes	no
159	2013	Yan <i>et al.</i>	Robust optimization model of bus transit network design with stochastic travel time	Minimize expected value and variability of operator cost	network structure; travel time data; demand matrix; route configuration constraints	network configuration; frequency; number of transfers	Simulated annealing	Benchmark	Mandl's benchmark network		Network design with the objective of obtaining robust arrivals under stochastic travel time	no	no	yes	no
160	2014	Amiripour <i>et al.</i>	Designing large-scale bus network with seasonal variations of demand	Minimize total waiting time, fleet size, total differences from the shortest path and empty seats hours	budget; max. unsatisfied demand; network structure; fleet size bounds; demand matrix (variable)	headways; deviation of shortest paths; number of transfers; network configuration; fleet size	Genetic algorithm	Real	Mashhad, Iran	756 nodes, 1204 links	Large-scale network - considers seasonal variation	no	no	yes	no
161	2014	Badia <i>et al.</i>	Competitive transit network design in cities with radial street patterns	Minimize total cost (user and operator)	demand distribution; transport technology; network structure	zone size; line and stop spacing; headways	Analytical	None	Sensitivity analysis			no	no	no	no
162	2014	Cooper <i>et al.</i>	Optimising large scale public transport network design problems using mixed-mode parallel multi-objective evolutionary algorithms	Minimize total cost (user and operator)	travel time matrix; demand matrix; road network	average travel time; network configuration	Parallel Genetic algorithms	Realistic	Cardiff, UK	70 bus stops		no	no	no	no

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163	2014	Ibeas et al.	Bus size and headways optimization model considering elastic demand	Minimize total cost (user and operator)	unit costs; demand matrix and passenger assignment (lower level)	headways; vehicle capacity; fleet size; demand assignment	Heuristic	Real	Santander, Spain	15 lines	Simultaneous optimization of headways and vehicle capacity	no	no	no	no
164	2014	Kenneth Loh	Factors Influencing Bus Network Design	Minimize total travel time (waiting time, in-vehicle travel time, transfer time)	demand matrix; network structure	frequencies; network configuration (node sequence, length); travel time	Heuristic	Real	Singapore bus network	401 bus routes		no	no	no	no
165	2014	Kiliç and Göh	A demand-based route generation algorithm for public transit network design	Minimize total cost (user and operator)	demand matrix; network structure;	number of transfers; demand satisfaction; average travel time; route length	Heuristic (multiple algorithms)	Benchmark	Mandl's benchmark network and comparison with results from previous authors			no	no	no	no
166	2014	Kim and Schonfeld	Integration of conventional and flexible bus services with timed transfers.	Minimize total cost (user, operator, and transfer)	demand matrix; region size	service type; fleet size and capacity; number of zones; headways; network configuration	Analytical	Example	Numerical analysis		Integration of coordinated (fixed) and uncoordinated (flexible) headways in transfer coordination	no	no	yes	no
167	2014	Martinez <i>et al.</i>	Frequency optimization in public transportation systems: formulation and metaheuristic approach.	Minimize overall travel time	demand matrix; network configuration; passenger assignment	headways; fleet size	Mixed integer linear programming and Tabu search	Real	Rivera and Montevideo, Uruguay	4945 nodes, 133 bus routes		no	no	yes	no
168	2014	Martynova et al.	Ant colony algorithm for rational transit network design of urban passenger transport	Maximize direct traveller density	demand matrix; network structure; network configuration constraints (route length)	network configuration; direct traveller density; number of transfers	Ant colony algorithm	Realistic	Numerical test (data from Tomsk, Russia)	38 lines, 900 stops		no	no	no	no
169	2014	Nayeem et al.	Transit network design by genetic algorithm with elitism	Minimize number of transfers and total travel time	network structure; demand matrix; travel time matrix	network configuration; average travel time; frequency; transfers	Genetic algorithm with elitism	Benchmark	Mandl's benchmark network and comparison with results from Mumford (2013)			no	no	yes	no
170	2014	Nikolic and Teodorovic	A simultaneous transit network design and frequency setting: computing with bees	Minimize travel time, number of transfers and fleet size	network structure; demand matrix; travel time matrix;	network configuration; fleet size; number of transfers; frequencies	Artificial bee colony algorithm	Benchmark	Mandl's benchmark network			no	no	yes	no
171	2014	Ouyang et al.	Continuum approximation approach to bus network design under spatially heterogeneous demand	Minimize total cost (user and operator)	network structure; average speed; unit costs; demand density	route spacing; headways; transfers; travel time	Analytical	Example	Model square city with different demand distributions			no	no	yes	no
172	2014	Schmid	Hybrid large neighbourhood search for the bus rapid transit route design problem	Minimize total passenger travel times	network structure; fleet size; vehicle capacity; demand matrix	network configuration; passenger density; frequency	Hybrid Metaheuristic (LNS, LP)	Test	Test based on data from Feillet et al. (2010)		Iterative solution with two different algorithms for route design (Large neighbourhood search) and frequency setting (Linear programming)	no	no	no	no

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173	2014	Szeto and Jiang	Transit route and frequency design: Bi-level modelling and hybrid artificial bee colony algorithm approach	Minimize number of transfers	travel time matrix; vehicle capacity; fleet size bounds; frequency bounds; network structure	transfers; waiting time; network configuration; frequency; fleet size	Artificial bee colony algorithm	Realistic	Tin Shui Wai, Hong Kong and Winnipeg, Canada	154 zones, 1067 nodes, and 2995 arcs (Winnipeg)		no	no	yes	no
174	2014	Tirachini et al.	Multimodal pricing and optimal design of urban public transport: The interplay between traffic congestion and bus crowding	Maximize social welfare (operator, bus user and car user costs)	network configuration; demand matrix	fares; frequencies; bus capacity and occupancy rate; modal split	Analytical	Real	Military Road in North Sydney, Australia	Single line with 12 zones	Multi-modal analysis (modal split between car, walking and bus) with pricing considerations	no	no	no	no
175	2014	Wu et al.	Modelling the coordinated operation between bus rapid transit and bus	Minimize total cost (user and operator)	network configuration; unit costs; demand data; vehicle capacity	system costs; headways	Genetic algorithm	Real	Beijing, China	1 BRT route, 8 feeder lines	Frequency optimization based on interaction between a trunk BRT route and various feeder lines through transfer stops	no	no	yes	no
176	2014	Yao et al.	Transit network design based on travel time reliability	Minimize passenger time cost, transfer time and reliability	demand matrix; network structure;	number of transfers; reliable travel time; network configuration	Tabu search	Example	Numerical example of small and medium sized networks			no	no	no	no
177	2014	Zhang et al.	Agent-based simulation and optimization of Urban transit system	Minimize operator cost (upper level) and passenger time cost (lower level)	network configuration	frequencies; passenger flow	Agent-based simulation	Test	Numerical examples		Focus on lower level (passenger decision) model	no	no	no	no
178	2015	An and Lo	Robust transit network design with stochastic demand considering development density	Minimize total cost	population density (demand) over time; network structure; user equilibrium; vehicle capacity; unit costs	network configuration; headways; passenger flows	Analytical	Example	Model linear network	8 nodes	Multimodal network of rapid transit lines and flexible bus feeder lines - consideration of land use and density	no	no	no	no
179	2015	Arbex and Da Cunha	Efficient transit network design and frequencies setting multi-objective optimization by alternating objective genetic algorithm	Minimize passenger and operator cost	network configuration; travel times; demand matrix	waiting times; number of transfers; unsatisfied demand; fleet size	Alternating Objective Genetic algorithm	Benchmark	Mandl's benchmark network			no	no	no	no
180	2015	Cancela, et al.	Mathematical programming formulations for transit network design	Maximize operator profit and user convenience (service coverage, total travel time)	passenger assignment model and demand matrix; network structure; fleet size; vehicle capacity	transfers; network configuration (length); headways	Mixed integer linear programming	Real	Rivera, Uruguay	13 lines, 84 nodes, 143 arcs and 378 OD-pairs		no	no	no	no
181	2015	Klier and Haase	Urban public transit network optimization with flexible demand	Maximize expected ridership	network structure; travel time matrix; budget; costs;	number of transfers; headways; network configuration; expected ridership	Analytical	Realistic	Dresden, Germany		No fixed demand matrix: consideration of influence of level of service on expected ridership	no	no	no	no

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182	2015	Pternea et al.	Sustainable urban transit network design	Minimize user and operator costs, minimize environmental impacts	network structure; frequency bounds; fleet size; vehicle typology	frequencies: network configuration; vehicle assignment; emissions; travel time	Mathematical and Metaheuristic (GA)	Real	Heraklion, Crete, Greece	10 lines, 50 stops, 100 buses	Consideration of mixed fleet of conventional and electric buses (and their limitations) as constraints to the TNDP	no	no	no	no
183	2015	Saleeshya and Anirudh	A bi-level approach to frequency optimisation of public transport systems	Minimize operator losses	network configuration; fleet capacity (bus type); demand data	fleet size; frequencies; travel time; operating costs	Artificial neural network (first level), Genetic algorithm (second level)	Example				no	no	no	no
184	2015	Verbas and Mahmassani	Integrated frequency allocation and user assignment in multi-modal transit networks: methodology and application to large-scale urban systems	Maximize waiting time savings	fleet size and capacity; budget; policy headways; network configuration	frequencies; total travel times; number of transfers	Heuristic (bi-level program)	Real	Chicago Transit Authority network (USA)	134 routes, 13754 nodes, 63602 arcs (multimodal network)	Bilevel solution framework	no	no	yes	no
185	2015	Verbas et al.	Stretching resources: sensitivity of optimal bus frequency allocation to stop-level demand elasticities	Maximize ridership and waiting time savings	demand elasticity; network configuration; fleet size and capacity; policy headways; unit costs	headways; ridership	Analytical	Realistic	Test based on Chicago bus network (large scale)	132 routes, 11,598 stops	Consideration of demand elasticity in frequency setting problems	no	no	yes	no
186	2015	Wang and Qu	Rural bus route design problem: Model development and case studies	Minimize route length	network structure	network configuration (route length)	Dynamic programming	Real	Pacific Pines (Suburb of Gold Coast, Australia)	Single line	Design of single suburban commuter line, demand and capacity considerations simplified	no	no	no	no
187	2015	Zhao et al.	The Memetic algorithm for the optimization of urban transit network	Minimize user cost and unsatisfied passenger demand	demand matrix; number of transfers; fleet size and capacity	route configuration; frequencies	Memetic algorithm	Benchmark	Mandl's benchmark network			no	no	no	no
188	2016	An and Lo	Two-phase stochastic program for transit network design under demand uncertainty	Minimize operating cost while satisfying demand	demand matrix; network structure; frequency bounds; unit costs	route configuration; frequencies; passenger flow;	Improved gradient method, Neighbourhood search	Benchmark	Benchmark networks		Combination of rigid (rapid transit) and flexible routes generated and optimized in two different phases	no	no	no	no
189	2016	Fouilhox et al.	Valid inequalities for the synchronization bus time-table problem	Maximize total number of synchronizations	network configuration; headway bounds	departure times; synchronization nodes	Mixed integer programming	Test			Difference between transfer nodes and congestion nodes and application of flexible headways to optimize transfers	no	no	no	no
190	2017	Griswold et al.	Optimizing urban bus transit network design can lead to greenhouse gas emissions reduction	Minimize total system costs and greenhouse gas emissions	demand density; fleet characteristics; emission factors	zone size; line spacing; headways; emissions	Continuum approximation	Real	Barcelona, Spain	11 lines	Extension of previous work by Daganzo (2010) and Estrada et al. (2011) to include analysis of GHG emissions	no	no	no	no

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191	2018	Boyer et al.	Vehicle and Crew Scheduling for Flexible Bus Transportation Systems	Minimize operating costs (drivers and vehicles)	labour regulations for drivers (max. driving hours, mandatory breaks); compatibility of trip-driver, vehicle-driver, and trip-vehicle pairs	driver working time (idle time plus driving time); vehicle cost	Variable neighbourhood search	Realistic	Data from Monterrey, Mexico	400 randomly generated sets based on real data	Considers a three-way compatibility between drivers, vehicles, and routes as constraints for operational optimization	no	no	no	no
192	2018	Buba and Lee	A differential evolution for simultaneous transit network design and frequency setting problem	Minimize user and operator costs	demand matrix; travel time matrix; existing road network; route length bounds; headway bounds; bus size	route configuration; travel time; headways; fleet size	Differential evolution algorithm (metaheuristic)	Benchmark	Mandl's benchmark network			no	no	no	no
193	2018	Ceder and Liu	Integrated public transport timetable synchronization and vehicle scheduling with demand assignment: A bi-objective bi-level model using deficit function approach	Minimize total travel time and fleet size	network configuration; demand matrix; travel time matrix; vehicle capacity; load factor constraints; average speed	fleet size; travel time; waiting time; departure times; demand assignment	Deficit function search method	Example	Medium-sized model city		Integration of timetabling and vehicle scheduling	no	no	no	no
194	2018	Krylatov and Shirokolobova	Evolutionary optimization of the public transit network	Minimize travel times and fleet capacity	demand matrix; existing road network; bus capacity	fleet size; travel time; number of routes; headways	Evolutionary algorithm (metaheuristic)	Real	Omsk, Russia	1280 bus stops, 151 routes	Case application reduced number of buses in operation and number of lines for similar travel time results	no	no	no	no
195	2018	Owais and Osman	Complete hierarchical multi-objective genetic algorithm for transit network design problem	Minimize user and operator costs	network structure; demand matrix (with uncertainty); route length; vehicle capacity	transfers; frequencies; fleet size; average travel time	Genetic algorithm	Realistic	Rivera, Uruguay and Mandl's benchmark network	84 nodes, 143 arcs and 378 O/D pairs		no	no	no	no
196	2018	Volotskiy et al.	An Accessibility Driven Evolutionary Transit Network Design Approach in the Multi-agent Simulation Environment	Maximize accessibility	network structure (zones, stops); subsidies; population density	network configuration (routes, stops); accessibility index	Agent based simulation	Real	Cottbus, Germany and Krasnoyarsk, Russia	33 routes	Accessibility maximization model focused on para-transit network	no	no	no	no
197	2019	Ahmed et al.	Solving urban transit route design problem using selection hyper-heuristics	Minimize passenger travel time and operator costs	network structure; travel time matrix; demand matrix;	network configuration; transfers; average travel time	Selection hyper-heuristics	Benchmark	Mandl's benchmark network			no	no	no	no
198	2019	Carosi et al.	A matheuristic for integrated timetabling and vehicle scheduling	Minimize user (timetabling) and operator costs (vehicle scheduling)	network configuration; headways (ideal)	headways; waiting time; travel time; dead-heading time; departure times	Matheuristic	Realistic	Milan, Italy	12 lines	Integration of timetabling and vehicle scheduling in a simultaneous approach	no	no	no	no
199	2019	Cipriani et al.	Transit network design for small-medium size cities	Minimize weighted sum of user and operator cost	network structure (roads, terminals); vehicle capacity; demand matrix	total travel time; transfers; fleet size; network configuration; frequency	Heuristic	Real	Foligno, Italy (55000 inhabitants)	16 bus lines	Consideration of specificities of small cities' urban form and the challenges they pose to bus network design, as well as	no	no	no	no

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											different passenger behaviour than larger cities				
200	2019	Duran et al.	Transit network design with pollution minimization	Minimize travel time and emissions	network structure; demand matrix (fixed); fleet size bounds; demand assignment	network structure; frequencies; fleet size; modal split; emissions	Genetic algorithm	Benchmark	Mandl's benchmark network and comparison with results from previous authors		Three problem definitions with increasing number of constraints, including incorporation of modal split between cars and buses	no	no	no	no
201	2019	Feng et al.	A new transit network design study in consideration of transfer time composition	Minimize travel time and number of transfers	demand matrix; travel time matrix; average walking times	network configuration; total travel time; number of transfers; transfer time; route length	Genetic algorithm	Example	Abstract bus network based on a medium Chinese city	344 bus stops, 39 lines	Topological generation of a bus network considering impact of variable transfer times in total travel time	no	no	no	no
202	2019	Islam et al.	A heuristic aided Stochastic Beam Search algorithm for solving the transit network design problem	Maximize demand satisfaction, minimize total travel time	demand matrix; travel time matrix; bus capacity; minimum frequency	network configuration; headways; total travel time; fleet size; ridership	Heuristic, Stochastic beam search	Benchmark	Mandl's benchmark network and comparison with results from previous authors			no	no	no	no
203	2019	Jha et al.	A multi-objective meta-heuristic approach for transit network design and frequency setting problem in a bus transit system	Minimize travel time and operating costs	road network; demand matrix; travel time matrix; fleet size; headway bounds; carbon emissions	route configuration; headways; number of transfers; demand satisfaction; average travel time	Metaheuristic (multi-objective particle swarm optimisation with multiple search strategies)	Benchmark	Mandl's benchmark network and comparison with results from previous authors			no	no	no	no
204	2019	Liang et al.	Bus transit network design with uncertainties on the basis of a metro network: A two-step model framework	Minimize user and operator costs	network structure; stochastic demand function; vehicle capacity; frequency bounds; existing schedules (metro); fleet size	network configuration; frequencies; passenger flows	Linear programming	Real	Beijing Second Ring public transit network	14 metro stations and 38 bus stops, 106 nodes and 1706 arcs	Coordinate bus and metro network under demand and travel time uncertainty	no	no	no	no
205	2019	Nayeem et al.	Solving Transit Network Design Problem Using Many-Objective Evolutionary Approach	Minimize travel and waiting time, transfers, fleet size, route length and unsatisfied demand	network structure (set); demand matrix; frequency bounds; vehicle capacity; network configuration constraints (routes, stops)	travel time; waiting time; transfers, fleet size; network configuration (length, overlap); frequencies	Evolutionary algorithm	Benchmark	Mandl's benchmark network			no	no	no	no
206	2019	Nnene et al.	Transit network design with meta-heuristic algorithms and agent-based simulation	Minimize user and operator cost	network structure (set); frequency bounds; network configuration constraints	network configuration; frequencies; demand assignment; travel time	Agent based simulation (metaheuristic)	Real	Cape Town, South Africa	472 nodes, 46 routes	Agent based simulation of demand and route choice as basis for network design	no	no	no	no
207	2019	Sun and Szeto	Optimal sectional fare and frequency settings for transit networks with elastic demand	Maximize operator profit	existing network configuration; frequency bounds; fare bounds; vehicle capacity; unit costs; demand function	frequencies; fares; demand assignment	Heuristic	Real	Tin Shui Wai, Hong Kong	7 nodes	Determination of sectional fares and frequencies with elastic demand	no	no	no	no

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												GH	KK	IR	FH
208	2019	Torabi and Salari	Limited-stop bus service: A strategy to reduce the unused capacity of a transit network	Minimize total fleet unused capacity and total travel time	vehicle capacity; travel time matrix; demand matrix; frequency bounds; ridership bounds	route configuration; passenger assignment; frequencies	Metaheuristic	Test			Optimize network configuration to minimize unused capacity while balancing user costs through service level constraints	no	no	no	no
209	2019	Wu et al.	Stochastic bus schedule coordination considering demand assignment and rerouting of passengers	Minimize user and operator costs	network configuration; unit costs; vehicle capacity; travel time matrix	headways; slack times; passenger flow distribution	Mixed integer programming	Example	Numerical example		Schedule coordination considering service disruptions and rerouting costs	no	no	no	no
210	2020	Abdolmaleki et al.	Transit timetable synchronization for transfer time minimization	Minimize total passenger waiting time	route structure; fixed headways; travel times	departure times	Approximation algorithm	Realistic	Mashhad, Iran (Shafahi and Khani, 2010)	139 two-way lines, 3618 stopping stations		no	no	no	no
211	2020	Chai and Liang	An Improved NSGA-II Algorithm for Transit Network Design and Frequency Setting Problem	Minimize passenger travel time and fleet size	bus capacity; route configuration and headway bounds	headways; fleet size	Genetic algorithm (NSGA-II)	Benchmark	Mandl's benchmark network			no	no	no	no
212	2020	Duran-Micco et al.	Considering emissions in the transit network design and frequency setting problem with a heterogeneous fleet	Minimize passenger travel time and CO2 emissions	unit costs and CO2 emissions; budget constraint (operator cost limitation); demand matrix (fixed)	number of transfers; frequencies; bus type assignment	Memetic algorithm	Benchmark	Benchmark networks		Travel time and emissions optimization through assignment of different bus types (different capacity and emissions) for each line	no	no	no	no
213	2020	Oliker and Bekhor	An infeasible start heuristic for the transit route network design problem	Minimize passenger travel time	fleet size; headway bounds; demand assignment	network configuration; headways; travel time	Heuristic (Infeasible start algorithm)	Real	Winnipeg, Canada	154 zones, 2975 links, 903 nodes	Candidate route generation in first phase and optimization and headway assignment in second phase. Operator cost as constraint and not objective	no	no	no	no
214	2020	Ranjbari et al.	A network design problem formulation and solution procedure for intercity transit services	Minimize passenger travel time and deadheading time	network structure; demand matrix; frequency bounds; vehicle capacity; unit costs	network configuration (number of routes); fleet size; frequencies; total travel time; demand coverage	Mixed integer linear programming	Real	Intercity bus service in Arizona, USA	22 terminals, 30 routes and 390 vehicles		no	no	no	no
215	2020	Shi and Gao	Analysis of a Flexible Transit Network in a Radial Street Pattern	Minimize overall system costs	unit costs; average speed; street pattern;	waiting time; travel time; number of routes; headways; fleet size	Genetic algorithm	Test	Sensitivity analysis and comparison with fixed models		Idealized evenly spaced ring routes as structure for flexible transit service	no	no	no	no
216	2020	Wu et al.	Optimal design of transit networks fed by shared bikes	Minimize user and operator costs	network structure; unit costs; headway bounds; vehicle capacity; average speed	station catchment area (walking/biking distance; station spacing); total travel times; capital and operating costs	Analytical	Test	Numerical analysis		Shared bikes considered as first and last mile transport as alternative to walking and feeder buses	no	no	no	no

N°	YEAR	AUTHOR(S)	TITLE	OBJECTIVES	CONSTRAINTS	DECISION VARIABLES	METHODOLOGY	APP. TYPE	APPLICATION CASE	SAMPLE SIZE	OBSERVATIONS	PRESENT IN:			
												GH	KK	IR	FH
217	2020	Zhang et al.	Transit route network design for low-mobility individuals using a hybrid metaheuristic approach	Minimize, transfer, and unsatisfied demand costs with priority for low mobility individuals	min/max headway and route length constraints; vehicle capacity and speed; fleet size	route length; headways; passenger assignment; travel times	Hybrid Metaheuristic	Realistic	Wenling, China		Priority given to accessibility of the network in the design phase	no	no	no	no

APPENDIX B

LEGEND

OBJECTIVE (MIN.)

UC – User Cost
AT – Access Time
TT – Travel Time
WT – Waiting Time
TR – Number of Transfers
OC – Operator Cost
FS – Fleet size
LF – Load Factor
DH – Deadheading Time
CO – Emissions
OO - Other

OBJECTIVE (MAX.)

CV – Coverage
TR – Potential Transfers
WF – Welfare
P€ – Profit
RI – Ridership
PF – Passenger Flow
OO – Other

CONSTRAINTS

DZ – Demand Data
DD – Demand Density
DF – Demand Function
DM – Demand Matrix
MS – Modal Split
PA – Passenger Arrival Rate
AS – Average Speed
BS – Vehicle Capacity
FS – Fleet Size
DW – Dwell Time
B€ - Budget Constraints
S€ - Subsidies
U€ - Unit Costs
EF – Existing Frequencies
NC – Existing Network Config.
ES – Existing Schedules
FR – Frequency Bounds
NX – Network Config. Constraints
NS – Network Structure
TT – Travel Time Matrix
CX – Driver Shift Constraints
CO – Emissions
LF – Load Factor
OO – Other

DECISION VARIABLES

RI – Ridership
DT – Departure Times
DR – Driver Shifts
€€ - Fares
F€ - Fixed Cost
FS – Fleet Size
FR - Frequencies
NW – Network Configuration
O€ - Operating Costs
OO – Other
DW – Dwell Time
VA – Vehicle Assignment
VC – Vehicle Capacity

PROBLEM TYPE

ND – Network Design
FS – Frequency Setting
TT – Timetabling
VS – Vehicle Scheduling
DS – Driver Scheduling

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[illegible]

[illegible]

[illegible]

100

[illegible]

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[illegible]

