TRANSIT NETWORK DESIGN AND SCHEDULING: A GLOBAL REVIEW

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Abstract: This paper presents a global review of the crucial strategic and tactical steps of transit planning: the design and scheduling of the network. These steps influence directly the quality of service through coverage and directness concerns but also the economic profitability of the system since operational costs are highly dependent on the network structure. We first exhibit the context and the goals of strategic and tactical transit planning. We then establish a terminology proposal in order to name sub-problems and thereby structure the review. Then, we propose a classification of 69 approaches dealing with the design, frequencies setting, timetabling of transit lines and their combinations. We provide a descriptive analysis of each work so as to highlight their main characteristics in the frame of a two-fold classification referencing both the problem tackled and the solution method used. Finally, we expose recent context evolutions and identify some trends for future research. This paper aims to contribute to unification of the field and constitutes a useful complement to the few existing reviews.
Keywords: Public transportation, Network design, Network scheduling

I. INTRODUCTION

Public transportation planning covers a very wide research area. From the design of networks to the rostering of crews, from the evaluation of demand to the transit trip assignment, from mathematical solution methods to evolutionary ones, the process of generating a public transportation system has been approached from many sides. This thorough interest is partly due to the fact that the development of public transportation is a crucial topic in the modern society. Confronted to traffic congestion, urban parking problems and increasing pollution, car drivers might consider switching to public transit if they had an affordable and good quality system at their disposal. It is the duty and goal of transit agencies to provide such conditions, by adequately adjusting their systems, so as to maximize the quality of service to users while minimizing the costs. Tradeoffs thus need to be made and this is where various optimization techniques come into the game. From the users' perspective, the system should meet the demand by providing cheap and direct service to passengers. Criteria for using public transport can also include vehicle and transfer terminal comfort, regularity, service coverage and frequency level. From the operator's perspective on the opposite, the objective is for the system to make as much profit as possible. It is the main challenge in transit planning to find an equilibrium between these conflicting objectives. As the literature assesses, the public transit planning process is usually divided in a sequence of five steps: (1) the design of routes, (2) the setting of frequencies, (3) the timetabling, (4) the vehicle scheduling and (5) the crew scheduling and rostering. This review addresses the three first and thus fundamental elements of the public transit planning process, also called strategic (step 1) and tactical (steps 2 and 3) planning, respectively. All the information needed by the passengers, namely the transit routes network, the frequencies and departure times, is determined during these phases. One could therefore think that these steps are essentially user-oriented. However, the problem remains multiobjective since financial objectives must also be taken into consideration. Even inside the restricted area of our problem, numerous approaches have been proposed, integrating different constraints, aiming for various objectives and combining heterogeneous features. In the domain of transit planning, several interesting reviews are available. focus mainly on mathematical methods for each individual steps of the planning process. present reviews of the transit network design problem as an introduction to their applied research. Finally, surveys the approaches limited to network design and frequencies setting used by British operators for urban bus services in the 80s.There are essentially three main reasons motivating this review. First, the previous reviews all gather interesting and useful information on a particular part of the whole transit network design and scheduling problem. However, it is difficult to apprehend more global problems and the way sub problem solution methods can be complementary or not. Second, the evolutionsin public transit policies, in particular the development of intermo dality, integration and deregulation, raise important new questions on transit planning. Third, the recent years have seen important advances in solution methods, leading to the development of innovative approaches whose efficiency deserves to be emphasized. This review thus aims at dealing with the transit network design and scheduling problem in the goal of providing the reader with a broader and more complete view of the field. Given that the domain does not possess a standardized convention for terminology, we will first propose a terminology for each of its sub-problems. We then establish a classification of the existing approaches according to two important criteria: the target problem and the solution method developed. Moreover, for each reviewed work, a descriptive analysis is given, so as to outline their characteristics, originality, application domain and limitations. For a complete appreciation and broader understanding of the domain, we open the review to another level of perspective by pointing out recent policy developments impacting transit network problems, and by proposing new challenges and opportunities for future work.

II. THE GLOBAL TRANSIT PLANNING PROCESS

General transit planning is an extremely complex and difficult problem; even its sub-problems considered separately are

already NP-hard from a computational complexity point of view (Magnanti et al., 1984; Quak, 2003). The first approach to the line planning problem was published more than 80 years ago (Patz, 1925) but more advanced and powerful methods

have been developed along the years. The global transit planning process is based on the following input: a public demand, an area with topologic characteristics, a set of buses and a set of drivers. The goal is to obtain a set of lines and associated timetables to which buses and drivers are assigned. According to Ceder and Wilson (1986), the global transit planning process can be decomposed into a sequence of five components as shown in. Ideally, all those steps should be treated simultaneously so as to ensure interaction and feedback, thus leading to better quality results. However, due to the exceptional complexity of the process, this global approach appears intractable in practice. As a result, various sub-problems have been defined over the years so as to solve the planning problem in a sequential manner, although it thereby loses any optimality guarantee. Our concern here relies on the first three steps of thisframework.

1. Transit network design

1.1 Purpose

The goal in this component is to define a set of bus routes in a particular area, each route being determined by a sequence of bus stops.

1.2. Input

Topology: The area's topology can be defined by the roads, possible areas for bus stops and transfer zones, and sometimes

also the location of depots that serve as extreme terminals.

Origin–destination (OD) matrices: OD matrices are needed to define a transit routes network that satisfies as much as possible the community's demand. An OD matrix has the set of stop points as coordinates. Rows correspond to the origins and columns to the destinations of the users. The OD matrix contains the number of passengers willing to go from each origin to each destination in a given time period. The more precise the data, the more adequate the solution; therefore, let us detail matrix characteristics that enhance results: matrix coordinates – coordinates of the matrices could correspond to the exact origin and destination wishes of the community. However, this is not realistic since buses cannot stop at every desired point but only at pre-defined bus stop locations. Therefore, OD matrices should have the set of possible transfer zones and bus stop locations as coordinates; survey conditions – to fulfill the expectations of all potential passengers, the survey should be led through the entire community and not only through the current users of public transport.

1.3. Main constraints and objectives

Depending on the politics of the transit agency, constraints and objectives might intermingle. Since there is no assessed rule to differentiate them, we list them as a unique set of features. Historical background: The existing network, if any, can play a role, in the sense that for some (political) reasons, it might be undesirable to disrupt service on already existing lines. Area coverage: It measures the percentage of the estimated demand that can be served by public transit. This ratio can be computed in several ways (Spasovic et al., 1993) but usually depends on characteristics such as route length, density, bus stop and route spacing (Murray, 2003; Benn, 1995). The rules-of-thumb often used consider that people living within 400–500 m from a bus stop are part of this percentage. Some plans (Murray et al., 1998) aim for a 90% ratio. Route and trip directness: Limits are imposed on the distance that one user can cover in the transit network with consideration to one's trip demand. From the users' point of view, the bus network should indeed enable them to travel as directly as possible from their origin to their destination and to walk the shortest distance to reach the first and final bus stops. Different definitions can be used to evaluate this feature. Directness can depend on the route's deviation from a linear path (Benn, 1995) considering the additional mileage incurred by a bus trip compared to the same trip by car or another means of transportation. The number of transfers is also a recurrent criterion. Note that to compute trip directness for each user, it is necessary to go through a passenger trip assignment process. This consists in assigning routes and transfers to passengers with respect to some objective such as shortest path or smallest number of transfers (Desaulniers and Hickman, 2007). Demand satisfaction: It is obviously a crucial issue. When users' origin or destination are too distant from bus stops, or when trip directness is insufficient, the demand can be considered unsatisfied. Note that similarly to trip directness evaluation, computing demand satisfaction requires to go through a transit trip assignment process. In a general manner, if a trip requires more than two transfers, it is assumed that the user will switch to another means of transportation. Number of lines or total route length: A general objective of the operator is to minimize the total route length in the perspective of reducing the number of vehicle and crew resources needed to sustain the global transit system. The number of lines can alternately be considered. Moreover, routes should neither be too short nor too long for profitability reasons.

Operator-specific objectives: For some reason, transit agencies may want to develop a network with a particular shape. Radial, rectangular, grid and triangular (Van Nes, 2002) are common shapes used.

2. Transit network frequencies setting

2.1. Purpose

This step provides frequencies for every line in the network and for each time period. As a consequence, the number of line runs are roughly defined during this phase. A line run corresponds to one scheduled service of the line. The inverse of the frequency over a determined period is called the headway. It corresponds to the time elapsing between consecutive line run departures.

2.2. Input
Transit routes network: The transit routes network constitutes the main input for the current matter. Public demand: Detailed OD matrices are needed in this step. They should provide data according to uniform demand time periods. These periods vary according to the following criteria: time of the day (peak/off-peak period), day of the week (Monday–Friday/Saturday–Sunday), time of the year (seasons/vacation periods/others). Since demand is time-dependent and elastic , the survey should be led on extensive periods of time and regularly updated. Such a process is necessary to achieve an efficient network with satisfying service. However, it represents a real charge for the transit agency, since collecting this data is a very complex and expensive task. Such data is therefore rarely freely available Bus fleet: In most approaches, line frequencies also depend on the available fleet size and buses capacities. In this case, a description of the vehicles used is needed, especially if the fleet is heterogeneous. The period-dependent bus running times associated to each route of the network must also be provided.

2.3. Main constraints and objectives
Demand satisfaction: The lines frequencies should match the demand at best so as to avoid overcrowding and excessively large headways, and thereby reduce waiting and transfer times. Number of line runs: The number of runs for each line is an example of the multiobjective nature of the problem. While from the operator's point of view, it is desirable to minimize this number for resource-related reasons, users for convenience wish to benefit from the widest offer of line runs. Headway bounds: The operator can be imposed minimum and/or maximum headways on some lines or areas by regulating authorities. Historical background: In a similar way , historical line runs can be imposed.

3. Transit network timetabling
3.1. Purpose
This step yields a timetable that includes departure times from all the stops served by each line run in the network. Each line run's timetable consists of a departure time from the initial terminal, the expected departure times from each bus stop on the route, and an expected arrival time at the final stop.

3.2. Input
Transit routes network: The transit routes network constitutes the main input for the current matter. Running times associated to this network are also necessary to compute the timetables. Public demand: The lines frequencies determined in the TNFS step define the time coverage of the line. Additionally, the level of importance of each transfer is needed to secure a better quality of service through the minimization of passengers waiting times. This level of importance can be deduced from detailed period-dependent OD matrices.

3.3. Main constraints and objectives
Demand satisfaction: Timetable setting permits to compute passengers travel time for the first time in the process. These values should be minimized to enhance the passengers' mobility. If they are too high for some particular trip demand, this one can be considered unsatisfied.

3.4. Vehicle scheduling
The purpose of this component is to obtain a feasible sequence of line runs, also called bus service, thereby determining the number of buses required for the considered period, usually of one day long. For further information on vehicle scheduling,
we refer to Bunte et al. (2006).

3.5. Crew scheduling and rostering
This component aims at assigning drivers to bus services. Each driver ends up with a timetable for a given period. The scheduling phase is usually based on a one day period while the rostering phase concerns longer periods so as to include other types of constraints, for instance maximum number of consecutive working days. For further information on crew scheduling and rostering, we refer to Wren and Rousseau (1993).

3.6. The focus in this review
Transit planning is a multiobjective problem, where the users' and the operator's interests conflict. In many countries, regulating authorities pay transport operators for their services. While the former require a certain level of quality of service, the latter wish to minimize their expenses. The usual practice for the regulating authorities consists in imposing lines with given route configuration and frequencies so as to secure a certain level of coverage in time and space, while the operator then adjusts the line runs departure times so as to match its resources employment in an economic manner. Consequently, transfer synchronization receives little concern. This is pretty damageable to the users: transfer synchronization is a crucial element of service quality, and it is entirely dependent on departure times setting. Therefore, timetables could be a criterion imposed to the operator the way routes and frequencies already are.
Considering this matter of fact, this review will concentrate on the first three steps of the planning process, namely the transit network design, frequencies setting and timetabling, also known as strategic and tactical planning. The two last steps (i.e. vehicle scheduling, crew scheduling and rostering), in contrast, are related to operational planning and will be left aside. The detail of the internal structure of our review area, the transit network design and scheduling, will be presented in the next section with the associated terminology.

III. CONCLUSION
In this review paper, we have presented a non-exhaustive classification and analysis of studies on public transport strategic and tactical planning. Sixty-nine reviewed references are quoted in the bibliography and provide an extensive overview of the advances in the field of transit network design and scheduling. A terminology proposal for describing the transit network design and scheduling

problems was made and has contributed in structuring the literature review. Indeed, the studies have been grouped first by problem tackled and then by solution method. Both theoretical and practical approaches have been considered and a descriptive analysis has been provided for each of them. This approach differs from most of the reviews we have read on the subject in that it considers and classifies all the works related to the determination of the data necessary to the transit users (namely the routes network, the frequencies and timetables) whatever the optimization methods used. We have put forward that the global problem is computationally intractable and can hardly be tackled at once, thus preventing to guarantee overall optimality. There are basically two ways to undertake this complex problem: innovative solution methods and pertinent problem subdivision. Features such as decision variables, objective function, constraints andassumptions must then be carefully chosen. A selection of benchmark references was also established. However, most of them consist of basic data and can mostly be used for algorithmic comparison purpose. For real-world applications, it would be preferable to get more detailed data, for instance matrices depending on uniform demand periods. Finally, we have highlighted a sample of paths that represent challenges in public transit planning systems. Indeed, interaction between researchers and transportation companies will continue to improve the efficiency of the methods and thereby the profits of the companies as well as the quality of service to the users

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