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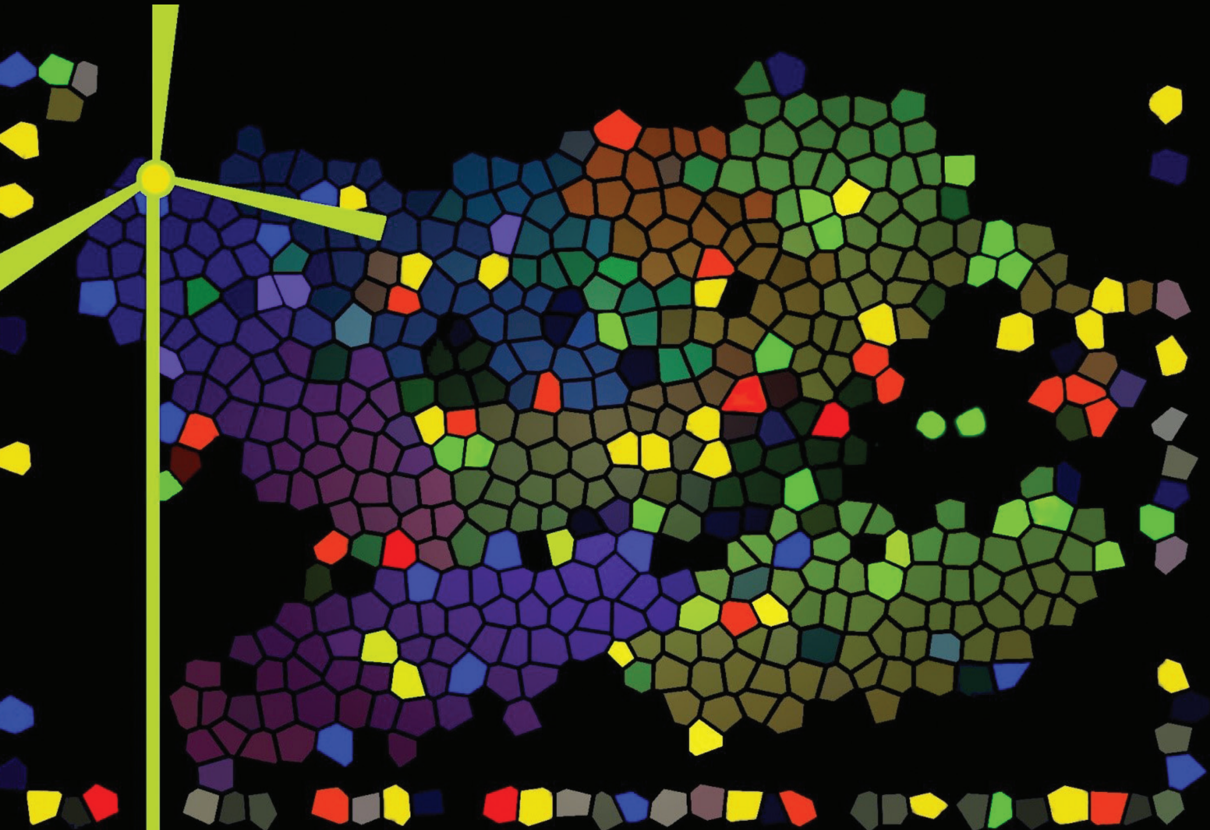

RELIABILITY METRICS FOR THE EVALUATION OF THE SCHEDULE PLAN IN PUBLIC TRANSPORTATION

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Abstract

Nowadays, the major Public Transportation Companies around the world use intelligent transportation systems based on automated data collection frameworks. The existence of these data has driven to the development of new approaches to the operational planning of public transportation. These approaches, commonly known as ADC-based operational planning strategies (ADC from Automated Data Collection), to improve public transportation reliability consist of adjusting the definitions made on the initial steps of the operational planning process by using real-world data. This type of changes concentrates mainly on restructuring routes and adjusting the existing schedule plan (SP). However, the usefulness of such tunings from a company point-of-view is often of difficult evaluation.

This paper starts by presenting a brief review on improving the network definition based on historical location-based data. Then, it presents a broad review on ADC-based evaluation techniques of the schedule plan reliability, discussing the existing metrics.

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The purpose of this paper is to critically describe the performance indicators used in the evaluation of the SP reliability, following the aforementioned bibliographic reviews. They will be certainly useful to shape the approaches developed by the research community for improving the quality of public road transportation operations based on data collected by ADC systems.

This paper focuses on two different, yet highly related, approaches: 1) changing the network definition; 2) evaluating and adjusting the SP in place. The automatic control strategies and the different actions to improve the SP remain out of the scope of this paper.

Keywords: Automated Data Collection (ADC); Operational Planning (OP); Public Transportation (PT); Network Design; Schedule Plan (SP); Reliability Metrics.

1. Introduction

In the last three decades, following a growing demand for fast transportation services in urban areas and clear advances both in real-time communications and in vehicle location technologies, public road transport companies have made important investments in information systems mostly dedicated to their operations (Furth *et al.*, 2003; Barabino *et al.*, 2013; Mazloumi *et al.*, 2010; Hounsell *et al.*, 2012). Automatic Vehicle Location (AVL), Automatic Passenger Counting (APC), Automatic Fare Collection (AFC), and multimodal traveler information systems are just some examples of this kind of answer from the operators to a major concern of reliability and service quality level from passengers. As a consequence of this effort in Advanced Public Transportation Systems, these companies have been able to collect massive data, indeed real continuous flows of data (Furth *et al.*, 2003).

The existence of these new data has driven to the development of new approaches for planning the operations of public transport companies, and many researchers have highlighted their potential to offer insights on new ways to evaluate and improve service reliability by means of both operational planning (OP) and control (Strathman *et al.*, 1999; Strathman, 2002; Strathman *et al.*, 2003). Some of these approaches imply changes in the initial phases of OP. However, the usefulness of such changes from a company view-point is not always easy to assess (Mendes-Moreira & de Sousa, 2014).

The aim of this paper is precisely to discuss works on the improvement of quality of public road transport operations based on OP strategies, mainly by using AVL and AFC data, and to improve the metrics and the approaches used in the evaluation of public transport reliability.

This paper starts with the presentation of how operational planning is usually done in public transport companies. Then, the next two sections are assigned to the review of literature; section 3 is dedicated to the alterations in the network design and section 4 to the evaluation of the schedule plan, both concerned with the reliability of the public transport service. Following the discussion presented in these two sections, challenges, opportunities and research ideas are proposed in section 5. Finally, in section 6, some highlights and thoughts on future research trends are synthesized.

2. Service and Operational Planning

Service and OP at public transport companies include network and route design, frequency determination, and vehicle and crew scheduling (Ceder, 2002; Wilson *et al.*, 2009):

a) *Network definition:* It consists of defining the *lines*, *routes*, and bus stops. Here, a route is an ordered sequence of directed road stretches between an origin and a destination, passing by multiple bus stops. A line is defined as a set of routes – typically two – with very similar paths, but inversely ordered.

b) *Trips definition:* The most common method involves firstly the definition of the set of bus stops for which schedule time-points will be set, necessarily including the origin and the destination ones. Then, timestamps are assigned to the previously defined schedule time-points. In high-frequency routes, however, this timetabling may also be defined by setting the time between two consecutive trips in the same route (this is called headway-based). The set of resulting trips is often defined as the *schedule plan* (SP).

c) *Definition of duties:* A duty is the work that a driver and/or a bus must perform in a day. The definition of the drivers' duties has much more constraints than the definition of bus duties (for instance, governmental legislation, union agreements and company rules). The logical definition of bus duties is commonly done prior to the drivers' duties.

d) *Assignment of duties:* It consists of physically assigning the previously defined logical duties to the companies' drivers and buses. The assignment of driver duties to drivers is called rostering.

Some authors (Vuchic, 2005; Ceder, 2007) also call this sequential or hierarchical process tactical planning. They claim that in the first stage of the process – the network design – decisions are less frequent; service considerations, judgement, and manual analysis tend to dominate. Going down the list, the dominance of these factors change up to the point where crew scheduling decisions are constantly made using cost considerations as the main driver and where computer-based analysis dominates in the optimization of the system (Aguerrebere, 2012).

Anyway, the data needed for this set of functions are extensive, encompassing all the inputs required for travel demand forecasting, as well as information on usage of the system and current route and network performance. And AVL and AFC data are most likely to be effective in characterizing this usage and the performance of the existing system (Wilson *et al.*, 2009).

There are internal and external causes for reliability problems arising in PT networks. The former are usually associated to persistent problems as they include factors such as route configuration, inappropriate scheduling, times for the entry and exit of passengers at bus stops. The external ones are more sporadic. They include traffic congestion and accidents, raining days or badly parked cars. Only the internal causes are addressed by means of OP strategies, trying to avoid unreliability on a long-term perspective. The sporadic problems are lessened by control strategies, ensuring just corrective actions for a specific situation in a given moment (Abkowitz & Tozzi, 1987).

In this paper we will only concentrate our attention in the internal causes and in the ADC-based OP strategies to improve the reliability of PT operations by using real-world data, since they facilitate the analysis of the supply and demand, while allowing new network proposals. This type of approaches focuses on (a) altering routes or restructuring the network or on (b) adjusting the existing SP.

3. On Modifying the Network Design

As previously mentioned in section 2, the PT network design consists mainly of defining the number of routes to build, along with their paths and bus stops.

The importance of the design and planning of the network structure for PT success is usually undervalued, and surprisingly the topic is more or less neglected in standard texts on public transport or transport policy (Nielsen & Lange, 2010). Maybe the infrequent nature of the network design can explain this underrating but getting the network right is usually more important than the often debated and studied mode selection.

Also, during the design stages of PT, little attention is paid to operational reliability, even if many design choices have a great influence on schedule observance. During the network design, reliability should be taken into account as a design parameter (Oort & Nes, 2009a).

It is clear that the data obtained from ADC systems can have wide-ranging applications within public transport. One of them, of particular interest, is the opportunity to make use of these databases to develop a better picture of how public transport systems are performing and being used (Wilson *et al.*, 2009). Better estimates of performance measures and usage attributes may be made at lower cost than by conventional methods, and, for the first time, it is possible to evaluate important attributes such as those concerned with reliability and its effects, until recently virtually impossible to quantify due to scarcity of data. Indeed, while there is an extensive bibliography about demand variations due to fare changes, findings on demand variations due to the level of service are occasional.

There are a few AVL-based works focused on improving the PT reliability by adjusting the route definition. The most common approach is changing the location of the bus stops. The work in Yan *et al.* (2006) used historical GPS data to mine human mobility patterns in a major Taiwan intercity bus operation to find an optimal compromise between the location of bus stops and operational costs. The researchers did so by discovering the demand patterns using both a stochastic demand scheduling model and heuristic-based methods to solve the models. A passenger wait cost-based model is developed in Li and Bertini (2008) to find the optimal bus stop spacing based on historical AVL data.

More recently, a couple of works were published showing that many cost-effective opportunities to improve the level of service reliability, together with the application of operational instruments, both related to network structure, lead to highly reliable services.

In Oort and Nes (2009a), a tool is developed to calculate the additional waiting time due to variability and transfers based on actual journey and passenger data. A case study in The Hague shows that in the case of long lines with large variability, splitting the line could result in less additional travel time because of improved reliability. This benefit compensates for the additional transfer time, provided that the transfer point is well chosen.

Public transport network planners often propose network structures that either assume a certain level of regularity or are even especially focused on improving service reliability, such as networks in which parts of lines share a common route or the introduction of short-turn services. The key idea is that travelers on that route will have a more frequent transit service. The impact of such network designs on service regularity is rarely analyzed in a quantitative way.

Oort and Nes (2009b) present a tool that can be used to assess the impact of network changes on the regularity on a transit route and on the level of transit demand. The tool can use actual data on the punctuality of the transit system. The application of such a tool is illustrated in two ways. A case study on introducing coordinated services shows that the use of such a tool leads to more realistic estimates than the traditional approach. Second, a set of graphs is developed which can be used for a quick scan when considering network changes. These graphs can be used to assess the effect of coordinating the schedules and of improving the punctuality.

Nielsen and Lange (2010) try to demonstrate the importance of network planning and design for the success of public transport. They present proposals for the structuring of multi-modal public travel networks in different types of urban and rural districts, and they also give examples of "good" practices from different regions and countries.

Also, Oort *et al.* (2013) describe the state of publicly available transit data, with an emphasis on the Dutch situation. The value of insights from Automatic Vehicle Location data is demonstrated by examples. A software tool, that makes comprehensive operational analysis possible for operators and public transport authorities, was able to identify several bottlenecks when applied in practice.

4. On Evaluating SP Reliability

In this section, the authors decided to follow quite closely the terms of the survey presented in Moreira-Matias *et al.* (2015).

The SP reliability is a vital component for service quality. Improvements on reliability may increase the service demand and, consequently, the companies' profitability. Low reliability levels lead to a limited growth in the number of passengers and to a decreased perceived comfort (Strathman *et al.*, 1999). It is possible to establish three distinct axes on evaluating SP reliability (Oort, 2011): 1) the unexpected increases on the waiting time on bus stops; 2) the time spent in crowded situations caused by transport overloading; and 3) delays on the passengers' arrivals due to travel time variability (TTV). The first two axes are mainly related with passengers' *comfort* and *experience* criteria. The value of such extra time consumptions varies from the passenger condition (seated or standing). However, these two aspects are mainly *satisfiers*: additional aspects that the passengers like to have but are not essential factors to abandon the services provided by a certain PT company. On the other hand, the last one is a fundamental issue by the disturbances that it does on the passengers' daily activities (Oort, 2011). By directly affecting the *convenience* and the *speed* of transportation, it is crucial to maintain the travelers' confidence on the PT network (i.e., a *dissatisfier*).

For the aforementioned reasons, this survey is focused on carrying the SP reliability evaluation by the existing TTV. Once established, it is expected that an SP meets the passengers' demand by *following* their mobility needs (namely, their daily routines). Typically, service unreliability is originated by one (or many) of the following causes (Fattouche, 2007; Cham, 2006): schedule deviations at the terminals, passenger load variability, running time variability, meteorological factors, and driver behavior.

Today's urban areas are characterized by a constant evolution of road networks, services provided, and location (for instance, new commercial and/or leisure facilities). Therefore, it is highly important to automatically assess how the SP suits the needs of an urban area. An efficient evaluation can lead to important changes in an SP. These changes will lead to a reduction in operational costs (for instance, by reducing the number of daily trips in a given route) and/or a reliability improvement in the entire transportation network, which will increase the quality of the passengers' experience and, therefore, the number of customers.

An SP consists of a set of *k* schedules, which provide detailed information about every trip running on previously defined routes. Each schedule contains a timetable. Different routes may have different timetables. Nevertheless, they share the number *k* of schedules and the daily *coverage* of each schedule.

A schedule planning process for a given route relies on three distinct steps: the first step is defining the number *k* of schedules and their individual coverage; second, the *schedule time-points* are chosen among all bus stops in the route; and finally, the third step is defining timetables for each route schedule containing the time the buses pass at each scheduled time-point (per trip). This process is done for all routes.

From the aforementioned definition of SP, it is possible to divide the SP evaluation into two different dimensions: the suitability of the number of schedules k and of the set of their daily coverages and the reliability of their timetables (to test whether the real arrival times of each vehicle at each bus stop are meeting the previously defined timetable). Although there is an obvious impact on the definition of the timetable, to the authors' best knowledge, until very recently there was no research reported in the literature addressing the evaluation of the number of schedules and their daily coverage (Mendes-Moreira *et al.*, 2015).

This section defines and reviews evaluation methodologies with regard to the reliability of timetables.

Evaluation Metrics

When evaluating an SP, it is important to differentiate *low-frequency services* and *high-frequency services* (Turnquist, 1982): in low frequency services, passengers arrive at the bus stops shortly before the bus's scheduled services, whereas in high-frequency services, the customers tend to arrive at the stops *randomly* (Jolliffe & Hutchinson, 1975; Turnquist, 1978; Bowman & Turnquist, 1981; Ceder & Marguier, 1985). In the first scenario, *punctuality* is the main metric, whereas the service *regularity* is the most important metric in high-frequency routes. There is no exact boundary between these two scenarios. Fan and Machemehl (2000) conducted a data-driven experiment in Austin, Texas (USA), where they identified a 10-min threshold. Recent studies have also used 10–12 min as a threshold between low and high frequency services (Oort, 2011; Trompet *et al.*, 2011).

Polus (1979) presented a landmark paper proposing four measures of performance for evaluating SP reliability on arterial routes: overall TT, congestion index, overall travel speed, and delay. All these measures were route based and highly focused on the operational perspective. The first three are mainly variations of the remaining ones – which are based on ratios between the actual and expected run times. Delay was a more sophisticated measure, defined as all the time consumed while traffic is impeded in its movement somehow – but also reported as hard to obtain by then.

The AVL data enabled the possibility to extend this analysis to other granularities than route based such as segment based or stop based. Following such advances, four main indicators were first proposed by Nakanishi (1997) and followed by other similar studies (Strathman *et al.*, 1999; Barabino *et al.*, 2013). These indicators are outlined as follows: 1) *on-time performance* (OTP); 2) *run time variation* (RVT); 3) *headway variation (HV)*; and 4) *excess waiting time (EWT)*. The first two indicators are more applicable to low-frequency routes, whereas the last two focus on the high-frequency routes (Turnquist, 1982; Strathman, 1998; Strathman *et al.*, 1999). This set of indicators is the most widely known formulations of these metrics, which have been used on multiple studies in the last decade. They are formally presented here.

OTP indicates the probability that buses will be where the schedule says they are supposed to be. It is possible to represent this metric by an *arrival delay* (AD) in a given trip i, i.e., AD_i as function of both the *scheduled arrival time*, i.e., SAT_i, and the *actual arrival time*, i.e., AAT_i. Therefore, it can be defined as follows (Strathman, 1998):

$AD_i = AAT_i - SAT_i$. (1)

The RTV represents the variation on the run times performed by each trip. Some introductory concepts on this subject will be presented below. Typically, the TT reports the trip duration, from terminal to terminal, and is often referred to as *round-trip time*. TT is often used to define the time required to go from one point of interest to the other. This last definition is used in this survey. One of the factors that mostly affect the RTV is the *dwell time*, which is the total time the bus has to stay at a given bus stop for passenger boarding and alighting. From the passenger perspective, a larger variation can mean a longer waiting time in some stops and/or missed transfers. From the operational planners' perspective, greater RTV translates into higher costs as a result of the extra hours that must be added to accommodate passenger load (Strathman, 1998). This indicator is more appropriate for routes that cover long distances, facing many traffic lights and regular traffic delays (Sterman & Schofer, 1976). Given a set of *n* trips of interest, it is possible to compute the RTV as follows (Strathman *et al.*, 1999):

$$\mathrm{RTV} = n^{-1} \text{ x } / \sum_{i=1}^{n} |\mathrm{SAT}_i - \mathrm{AAT}_i| \, / \, \mathrm{AAT}_i \quad (2)$$

In high-frequency routes, where the trips start within very short headways, the OTP is not that relevant (Hounsell & McLeod, 1998). The HV represents the probability that controllers are able to maintain a regular and stable headway between each pair of vehicles running in the same routes.

Let $f_{i,j}$ be the frequency (i.e., scheduled headway) established between a given pair of trips (i, j), whereas $H^{b}_{i,j}$ represents the observed headway on such pair of trips at a bus stop of interest, i.e., b. The *headway ratio* on the bus stop b, i.e., $\mathrm{Hr}^{\mathrm{b}}_{\mathrm{i,j}}$, is defined as follows (Strathman *et al.*, 1999; Strathman, 1998):

$$\mathrm{Hr}^{\mathrm{b}}_{\mathrm{i,j}} = \left(\frac{H^{b}_{i,j}}{f^{b}_{i,j}}\right) \text{ x } 100 \quad (3)$$

where the value 100 represents a perfect SP matching. Given a set of *n* trips of interest, it is possible to compute the standard deviation and the mean value of Hr ($\sigma^{\mathrm{b}}_{\mathrm{Hr}}$ and $\mu^{\mathrm{b}}_{\mathrm{Hr}}$, respectively). We can do it by calculating every possible $\mathrm{Hr}_{i,i+1}$: $i \in \{1, \ldots, n-1\}$ at a bus stop *b*. Then, it is possible to obtain the HV at bus stop b throughout these *n* trips as follows (Lesley, 1975):

$$\mathrm{HV}^{b} = \left(\frac{\sigma^{b}_{\mathrm{Hr}}}{\mu^{b}_{\mathrm{Hr}}}\right). \quad (4)$$

The EWT is an estimation of the excessive waiting time that passengers experience as a consequence of unreliable service. It is possible to calculate the EWT at a bus stop *b*, i.e., EWT^{b}, as a function of HV^{b}. A possible way to do so is presented as follows (Welding, 1957):

$$\mathrm{EWT}^{b} = \left(\frac{{\sigma^{b}_{\mathrm{Hr}}}^{2}}{2 \text{ x } \mu^{b}_{\mathrm{Hr}}}\right). \quad (5)$$

The bus stop *b* used to compute statistics on the first two indicators is the destination bus stop. For the last two indicators, any bus stop can be considered a reference if it has a frequency scheduled to it, i.e., $f^{b}_{i,j}$. Commonly, such statistics are computed by the transit companies aggregating its values to a fixed time granularity (typically, 1-h periods) (Barabino *et al.*, 2013), but they can be also computed according to the trip.

SP Evaluation Studies

Many works have evaluated schedule reliability by measuring the aforementioned indicators on historical AVL data sets. Strathman (1998) and Strathman *et al.* (1999) evaluated schedule reliability on the Tri-Met by measuring indicators (1–4), whereas the work by Bertini *et al.* (2003) solely focuses on the first two ratios. Traditionally, the HV was often disregarded by the transit planners due to the intrinsic *chaos* assumed (as the schedule time-points on the timetables are not the central variable to confirm service reliability). Nevertheless, recent advances have changed this reality: in Strathman *et al.* (2003), AVL/APC data were considered to evaluate the impact of the HV on the operational control. Another perspective of the Tri-Met data is presented in Berkow *et al.* (2007), where an analysis of indicators (2–4) demonstrated the feasibility of using AVL data along with other data sources to better accomplish their evaluation. Lin and Ruan (2009) formulated probabilistic headway regularity metrics (HV). Then, the authors tested their approach using AVL data from Chicago. In Bellei and Gkoumas (2010), relations between transit assignment, bus bunching events, and operation models are mined from the location-based data. This study aimed to identify irregularities in HV's distribution function caused by an inadequate SP. The reliability of an express service implemented in Montreal, Canada, is evaluated in El-Geneidy and Surprenant-Legault (2010) by employing the first two indicators. A large-scale evaluation was performed by Hounsell *et al.* (2012), where the data acquired through the *iBus* (an AVL/APC framework installed on a bus fleet running in the city of London, U.K.) were used to evaluate all the four main indicators of schedule reliability.

Another approach to evaluate schedule reliability on a route is the segment-based one. It consists of identifying segments/parts of a route where there are greater schedule deviations, and therefore, the SP should be adjusted by changing the timetable or by introducing bus priority lanes and/or traffic signals in intersections. One of the first authors to carry out such work was Horbury (1999) based on the HV. In Mandelzys and Hellinga (2010), it is proposed to measure indicators (1 and 2) using stop-based metrics and to identify the causes for larger deviations through an empirical framework. The work of El-Geneidy *et al.* (2011) proposes a way of identifying *where* the schedule is unreliable by evaluating the first two indicators on the schedule time-points.

Recently, the methodological approach to evaluate SP reliability has evolved from the key indicators to using nonparametric deterministic methods such as data envelopment analysis (DEA), as described in Mendes-Moreira and de Sousa (2014). The main advantage enabled by employing such a method is the possibility of directly comparing metrics from distinct dimensions by introducing decision-making units. Lin *et al.* (2008) used AVL data to establish confidence intervals for the DEA scores based on the four indicators previously introduced. Despite its usefulness in identifying cost-based relationships between the resources used and the service produced, the DEA models are not addressed in this survey as they usually use a wider scope of data on the companies' management than we do.

Many of the aforementioned works have often employed the four traditional transit measures to evaluate schedule reliability. Nevertheless, few works have been successful in identifying the factors behind poor performance measurements. Such measurements focus mainly on the passengers' perspective about the service. Recently, innovative approaches have emerged on this research topic, such as the day-to-day variability. Mazloumi *et al.* (2010) proposed to determine the nature and shape of TT distributions for different departure time windows at different times of the day, using data from a route running in Melbourne, Australia. Factors causing TTV in public transport are also explored using regression methods. A method for finding interesting contexts to justify RTV is proposed in Jorge *et al.* (2012): Distribution rules are employed to identify particular conditions that lead to systematic bus delays. The HV is explored using a sequence mining approach in Moreira-Matias *et al.* (2012). The goal is to highlight sequences of bus stops where a failure to meet the schedule systematically leads to bus bunching situations further stops ahead in the route. Recently, an innovative study was presented by Chen *et al.* (2009), where three novel metrics were proposed to address three distinct granularities, namely, stop, route, and network levels. This approach seems promising. However, it also fails to deliver a unique indicator on the SP reliability.

The contribution of this ongoing generator of historical trip data to evaluate SP reliability is that it replaces the old estimations on TTV with real values (Bertini & El-Geneidy, 2003). The findings of the evaluations previously described consisted of identifying unreliable schedule time-points (El-Geneidy *et al.*, 2011; Jorge *et al.*, 2012) or badly designed bus priority lanes (Hounsell *et al.*, 2012). In this work, some evaluations also build dwell time models that help to understand how this variable changes from trip to trip and throughout the day.

The four metrics are well established in the literature. However, they focus mainly on the passengers' perception of service quality, particularly the EWT. The OTP can help the planners identify the *exact* schedule time-points to be changed, whereas the RTV shows a more general perspective on network service, which can lead to more profound studies on the drivers' behavior, terminal dispatching policies, or on the current schedule's slack. The HV is the most used metric. Even so, it is possible to observe that the company's perspective on such RTV is not addressed as a primary goal of these evaluation studies.

Nevertheless, even if it is possible to identify *what* is happening and *where* changes must be performed to improve SP reliability, it is not easy to identify *how* it is possible to improve it.

5. Research Challenges

Two main issues may be identified where further AVL-based research should be employed to improve the evaluation of SP reliability: (a) creating a unique evaluation indicator, considering the company's perspective on the evaluation by including external factors in the evaluations or by developing cost-related evaluations and to (b) evaluate the reliability of the current schedule's number and coverage.

The aforementioned four evaluation metrics are classical but widely used in evaluation studies. However, distinct metrics (which are highly correlated to the main ones) are continuously emerging. It is known that the importance of each one of these indicators *depends* on the frequency established in the route. However, to the author's best knowledge, there is no consensual, individual, and integrated reliability ratio. This gap in the literature leads to an important research question: *Is it possible to build a consensual frequency-dependent reliability ratio based on these four main indicators?*

The first step in building an SP is defining both the schedule's number and day coverage. Then, a timetable is assigned to each schedule in a stepwise process already discussed. This definition has an explicit impact on the definition of timetables. However, to the authors' best knowledge, no research addresses the evaluation of whether the schedule's number and coverage still suit the current demand patterns and network behavior. Consequently, a question arises: *Is it possible to assess whether the schedule's number and coverage are suitable for the network needs based on historical AVL data?*

Another topic that can be a challenge is to rethink the OP. Section 2 briefly revises the steps of the traditional OP. Although AVL-based research has recently emerged on improving route definition, most AVL-based works on OP focus on the SP. The state of the art relies on deterministic and cost-based models. The AVL data make it possible to perform a bottom-up OP evaluation, namely, correctly exploring the available resources or even reducing them if possible to meet the current demand. A complete AVL-based framework to redesign all the steps of the OP is an intelligent transportation system (ITS) that could be a research goal on this topic for the medium-term future.

6. Conclusion and Future Trends

Over the last decade, various relevant contributions have emerged on location-based ITS applications for improving the OP of mass transit transportation networks. The spatiotemporal features of this type of data provided novel opportunities to reveal underlying patterns on unexpected behaviors that are deteriorating the quality of the service. These data are now affordable and widely available as a standard in every medium/large-sized mass transit company.

Such innovation revolutionized the way to improve both operational planning and control in these networks. The theoretical traffic models, which were the state of the art for improving OP during the 1980s and 1990s are now being progressively replaced by complex yet efficient statistical and machine learning models.

It is also important to provide real-time information to the passengers about what is *happening* in the network (i.e., on-the-spot information on arrival times). More than building an exact but time-consuming prediction on arrival time, the researchers have focused on building simple frameworks capable of learning from location-based data streams and of providing predictions with low uncertainty.

The AVL-based improvements to planning and control are becoming increasingly mature, but the existing evaluation studies are still mainly proofs of concept focused on the passengers' perspective. Some challenges have been addressed in the previous section.

The high availability of reliable data reporting the vehicle operations in real time pushes up the will of researchers in this field. It is expectable that data driven models will prove themselves as state-of-the-art methods for improving PT reliability. More than ever, the AVL data are a real-time stream. Such availability, along with the expansion of urban centers, can progressively change the traditional focus on planning to an autonomous data-driven real-time control, which may reduce the manpower required for those tasks.

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