An Offline Framework for the Diagnosis of Transfer Reliability Using Automatic Vehicle Location Data

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Abstract—In public transit networks, transfers occur when more than one route is used to connect origins and destinations. Much research has been done to investigate the design and management of transfers at the tactical and operational levels. However, very few studies have investigated the monitoring phase to check a posteriori if transfers are well planned and/or delivered according to archived automatic vehicle location (AVL) data. This article covers this gap by proposing the first offline framework. This framework preprocesses AVL raw data, performs a diagnosis of transfer reliability over all bus stops and time periods, and discloses the most common sources of transfer unreliability. Easy-to-read control dashboards show the viability of this framework on real bus routes with approximately 145,000 AVL data records to make an accurate transfer analysis and possible service adjustments.

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Transit service reliability is a relevant topic for passengers, operators, and transit agencies in terms of multidimensional aspects, such as passenger loads, vehicle quality, safety, amenities, information, and riding and waiting times [1]–[4]. When passengers need to switch between routes, they must pay attention to transfer reliability, accounting for both waiting and possible walking times between close bus stops.

To begin with, transfers aim to reduce the inconvenience to passengers if no direct route is available to connect the origin and the destination, and/or they need to use several transport modes (e.g., trams and buses). Thus, when passengers shift among routes, it is crucial to plan well-connected and synchronized transfers to minimize the transfer time, which is the waiting time plus the possible walking time, if any. This problem is relevant in the case of large and medium networks because transfers cannot be eliminated as well as in small networks with few skeleton high-frequency routes linked to feeder low-frequency services.

Second, the successful realization of transfers (or successful transfers) may help improve the characteristics of transit networks because they increase the connectivity of transit routes. Well-connected and synchronized transfers increase the number of suitable paths for passengers and, sometimes improve the transportation infrastructure by being an efficient resource allocation [1].

Nevertheless, transfers result in several inconveniences for passengers because they 1) may be requested to walk between the previous and the following route, 2) may negatively perceive the additional waiting time for the next vehicle, and 3) may experience possible delays during the trip. These inconveniences can be limited by designing, managing, and monitoring well-connected transfers for passengers.

Despite the abundance of research on the design and management of transfer, its monitoring has been seldom addressed. The challenge of designing synchronized transfers is faced at the tactical level. This research has largely focused on the minimization of the total passenger transfer waiting time or on the maximization of the total number of transfers. Different approaches have been adopted: 1) interactive graphical optimization [5], [6]; 2) analytical modeling [7]–[13]; and 3) mathematical programming methods [14]–[26].

The abundance of automatic vehicle location (AVL) and automatic passenger counting (APC) has enabled the tracking of vehicles and recording of passenger volumes [27]. As a result, recent research has attempted to implement real-time tactics to regulate the movement of vehicles at the operational level to maintain the planned (synchronized) timetable [28]–[33].

To the best of our knowledge, were it not for the work in [34], no study would have investigated the monitoring of transfers to check a posteriori if they were well planned according to AVL data. Moreover, no study has investigated the occurrence of unreliability sources due to missed transfers using archived AVL data, e.g., to possibly revise the service. As a result, proper service monitoring would help transit managers to concentrate their efforts on areas where targets are not met.

This article contributes to the advancement of the monitoring of transfers by a framework based on archived AVL data. It is organized into three stages (i.e., A–C):

A) preprocessing AVL raw data to obtain a set of adjusted data (i.e., without inconsistencies)
B) performing a diagnosis of transfer reliability to characterize bus stops and time periods where scheduled and actual transfers are not met
C) discovering possible sources of transfer unreliability from the measurement of regularity and/or punctuality and the causes observed in the specific routes at hand.

Although stage A) uses algorithms successfully applied for the characterization of reliability [35], [36], stage B) differs from all previous studies on transfers at both tactical and operational levels. Moreover, it advances the research by the authors in [34] to investigate the successfulness of a real transfer against the scheduled one while addressing anomalies in AVL raw data to avoid inconsistent measures. In addition, all previous studies considered a transfer a shared stop (or multiple shared stops), where several routes encounter. Unlike in [34], stage B) includes transfers between bus stops at an acceptable walking distance, which are denoted as unshared. They are often observed in real networks when two routes are not directly connected (e.g. owing to topographic structures). Finally, even if stage C) uses algorithms successfully applied in the diagnosis of the unreliability of the service for a single route (e.g., in [37] and [38]), it extends the domain of application (when multiple pairs of routes are considered). Furthermore, easy-to-read control dashboards present the outcomes through tables and diagrams organized in time-and-space attributes.

To the best of our knowledge, this article sheds new light on a research area that has not been completely addressed. This research is relevant for the transit industry for several scopes. First, a potential use of the diagnosis of transfer is the revision of the schedule of routes. Often, the public transport companies (PTCs) dispatch times of each route in isolation because only very few scheduled transfers are met. Second, the PTCs may certify the service quality on routes according to European norms [39], [40]. This process is handled by a third party that certifies quality outcomes. If ad hoc agreements are established on the achievement of pre-established levels of quality between PTCs and subsidizing agencies, financial gains can be realized. Because the transfer is one of the possible parameters for the certification of a route (e.g., [41]), its diagnosis is helpful for this purpose.

Literature Review

Over the last several decades, much research has been conducted on a variety of approaches to design, manage, and monitor transfers among routes, encompassing several transit modes, such as bus, rail, and so on.

Transfers at the Tactical Level

At the tactical level, one aims to plan the departure times (or timetables) and/or dispatch headways among bus routes within a given cycle time to achieve maximum synchronism among routes meeting at shared bus stops. According to the work in [42], this planning stage is conducted using 1) interactive graphical optimization, 2) analytical modeling, and 3) mathematical programming.

In 1), interactive graphic methods are proposed for the minimization of transfer delays in a transit network. For instance, Rapp and Gehner [5] determined an optimal, systemwide timetable coordination—including operational cost-based constraints—by computing the deviations from the original departure times. Désilets and Rousseau [6] proposed SYNCRO, a software designed for the synchronization of transfers.

In 2), elegant analytical model formulations are presented for idealized public transport systems. The core objective of these models is to clearly show the relationships between several transit system parameters and the demand for transit, operating costs, and so forth. Usually, these models attempt to optimize an objective function that represents the sum of the transit operating costs and passenger (time) costs [7]–[13]. Different networks are considered, such as ring-radial grid [7], rectangular [8], trunk and feeder routes [12], as well as integrations among modes of transport, such as bus and rail [9], [10]. For instance, the authors in [11] investigated the optimal setting of headways and slack times to minimize the total cost on a multihub transit network. Sivakumaran et al. [12] explored how the synchronization of timetables among vehicles affects the generalized costs by using some models. Kim and Schonfeld [13] proposed several models to deal with stochasticity in travel and waiting times to integrate and synchronize bus transit services for one terminal and multiple local regions based on the given demand.

In the wide area of mathematical programming models [that is, in 3)], an objective function is optimized while respecting several constraints. Generally speaking, the literature may be classified according to two different objective functions.

In the first, the problem is the determination of the departure times of the daily trips by the minimization of total passenger transfer waiting times [14]–[17] and [20]–[22]. In the second, the problem is the maximization of the number of synchronizations at shared stops from given dispatching headways [18], [19], [23], [24]. Because of their computational intractability, all of these models can be solved with heuristic methods only. Other works have overcome the synchronization problem by using data collected from different sources. For instance, Wang et al. [25] proposed a smart card data-driven model to schedule the departure time of each bus service to minimize the total passenger waiting time. Gkiotsalitis et al. [26] formulated the multiroute synchronization problem as a robust model with stochastic variations of travel and dwell times. They validated their approach in the bus network of The Hague using AVL/APC data and discussed potential improvements in service regularity and increased synchronizations.

Transfers at the Operational Level

At the operational level, the goal is to implement real-time tactics to select the best dispatching policies. As pointed out by the authors in [42], this approach includes research based on control theory models. Here, the issue of transfers' synchronization is the regulation—in real time—of the movement of vehicles in the network by improving the service reliability, schedule, and headway regularity of a planned synchronized timetable. Models were typically applied to evaluate the feasibility of operational control strategies, such as holding, skip-stop, short turn, and so on [28]–[32]. Usually, these models were simulated on possible case studies.

Other research proposed cooperative control strategies to help improve the reliability of routes. Daganzo and Pilachowski [43] proposed an adaptive control scheme to adjust the bus cruising speed in real time based on both its front and rear spacings, as if successive bus pairs were connected by springs. Liu and Ceder [33] offered a communication-based cooperative control strategy that selects operational tactics (e.g., skip-stops and changes in speed.)

Monitoring of Transfers

Finally, in the monitoring phase, one aims to measure the effect of shared bus stops on the transfer reliability by evaluating the success rate of well-planned transfer synchronizations. The research on this phase is nearly absent. To the best of our knowledge, only the authors in [34] have developed a tool that helps identify successful (or unsuccessful) scheduled transfers and the actions required to reduce or eliminate these failures, in the case of multiple shared bus stops. From AVL data Hadas 1) identified successful transfers in the planned service of timetable- and frequency-based routes, 2) showed that multiple shared bus stops can increase the chances of a synchronized transfer, and 3) estimated which bus stops can improve transfer chances by making an adjustment to the contact period.

Despite data abundance, AVL data require additional processing to correct possible anomalies: 1) missing data points, such as a technical failure (TF) and incorrect operation in service (IOS), and 2) bus overtaking (BO). A bus generates an IOS whenever it does not arrive at a bus stop, whereas a TF is a failed registration of AVL data. Conversely, in the case of a swap of buses with respect to the original schedule, a BO is observed. Moreover, although the occurrence of a TF depends on AVL architectures, that of a BO and an IOS concerns the operations within the service. Although a TF might be reduced by using complex AVL architectures with redundancy systems [44], [45], none of these guarantee the full detection of all vehicles. Nevertheless, all of these anomalies always affect raw AVL data, and they need to be recognized and adjusted before computing each measure [46].

Furthermore, much research has been carried out to evaluate the reliability (also affecting transfers) using several metrics [1], [37], [38], [47]. Typically, these metrics include on-time performance [48]–[51]; headway adherence [35], [52], [53]; running time distribution [4], [49], [54]; early and late departures/arrivals [49]; the occurrence and distribution of bunching [49], [55], [56]; and other metrics [36], [47], [51], [57]–[60]. Synthetic metrics outputs can be often expressed in terms of minimum (min), maximum (max), and mean values and variance, coefficient of variation, the percentage of observation, and related percentiles. In fact, they are widely used and well understood by PTCs and clearly represented by quantification. Furthermore, as many facets of reliability exist, many metrics can be adopted, showing the significant lack of a general metric.

Gaps in the Literature

All of the previous studies have presented fascinating models, methodologies, and findings on the design of timetables and the implementation of real-time tactics to select the best dispatching policies. However, the monitoring of transfers using AVL data has only been carried out by Hadas in [34], and significant room for improvement exists in this field. That paper neglected the frequent cases in which a transfer may occur at stops near each other at an acceptable walking distance. Moreover, Hadas [34] did not investigate the cases in which real transfers may match with scheduled ones to measure their ratio of effectiveness. Yet, the possible anomalies in AVL data were disregarded to avoid incorrect measures. Although many efforts have been devoted to reducing the occurrence of unreliability at the operational—real-time—control, no study has investigated the occurrence of unreliability sources of missed transfers (starting from the measurement and the causes observed in the routes at hand) using archived AVL data. This article seeks to fill in the gaps.

Methodological Framework

In this section, we propose a novel framework for the diagnosis of the reliability of transfers made at bus stops to switch between different routes. This framework preprocesses AVL data, performs an analysis of transfer reliability, and identifies (i.e., detects and evaluates) possible unreliability sources. The framework can operate on multiple pairs of routes and bus stops, which can be shared or unshared. A shared bus stop is an arrival and departure point for several routes such that passengers are requested to alight from the origin route, wait, and board to the destination route. An unshared bus stop is a collection of bus stops at an acceptable distance such that passengers are also required to walk to transit from the origin route to the destination route.

Figure 1 shows an example of a shared bus stop for three routes, denoted as A, B, and C, and three unshared bus stops, which are located at an admissible walking distance and can be used to make transfers between routes D, E, and F. Therefore, passengers need to wait to transfer in a shared bus stop and must walk and wait to transfer between unshared bus stops.

In both situations, passengers are supposed to switch from one route to another at most. As a result, only the following transfers can occur in Figure 1: in the shared bus stop from route A to B and vice versa, from route A to C and vice versa, and from route B to C and vice versa; and in the case of unshared bus stops from route D to E and vice versa, from route E to F and vice versa, and from route F to D and vice versa.

Although one could be interested in evaluating all the transfers in a (shared or unshared) bus stop, the framework focuses on the transfer between a pair of routes at a time. Indeed, the aggregate analysis of transfers in a (shared and unshared) bus stop neglects details on which ones are well or poorly performed. For example, there may be a successful transfer between route A and B, but it may not be so for the transfer between routes C and A. Without any loss of generality, in what follows, the framework is presented for any pair of route A and B. This framework is organized into three stages (that is, A–C):

A) AVL data preprocessing
B) Diagnosis of transfer reliability
C) Diagnosis of unreliability sources.

These stages interact with each other according to the scheme illustrated in Figure 2. The figure shows how to switch from AVL data processing to the evaluation of the transfer's reliability and the complete list of problem sources if a transfer is not adequate in real operations. This article focuses on unsuccessful transfers inferred from a standard AVL data architecture, even if some of them have could be reasonably detected from other data sources (e.g., the bus was suddenly not in service).

Figure 2 shows that three different types of transfers may be considered: candidate, scheduled, and real. The candidate transfer represents all the possible connections between two routes, both in terms of space (at shared and unshared bus stops within an acceptable walking distance) and time (within a maximum time, including waiting time at shared bus stops and the walking and waiting times at unshared bus stops).

The scheduled transfer represents all the feasible transfers, including the simultaneous arrivals detected in the

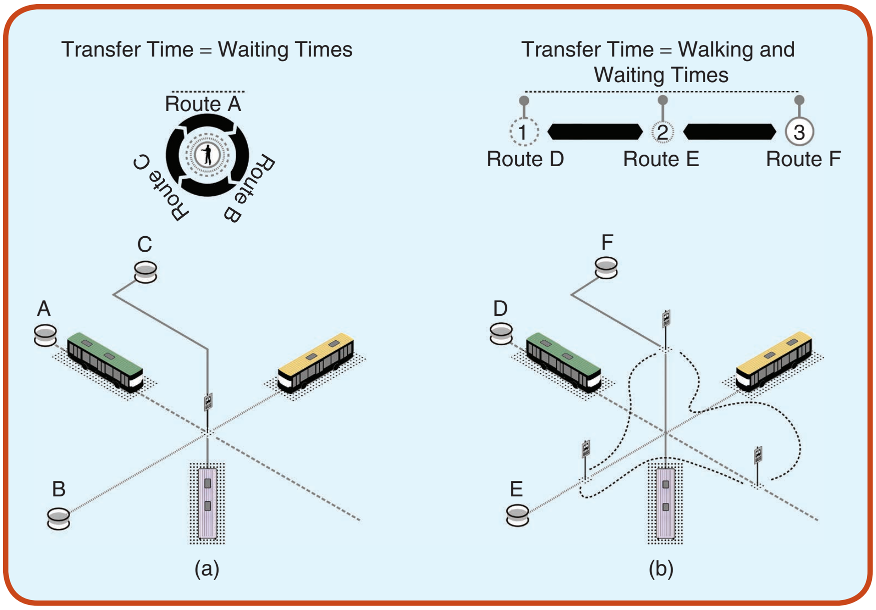


FIG 1 The (a) shared and (b) unshared bus stop.

original schedule. According to the definition by Eranki, "… they represent the arrival of two buses in such a way that the time gap between the arrivals does not exceed a tolerable waiting time." [19]

This definition is reasonable from a pragmatic viewpoint. First, due to uncertainties with the transit service, passengers generally prefer having a minimum transfer-waiting time. Second, our framework includes both shared and unshared bus stops; therefore, a maximum admissible time should be included to make unshared transfers successful. For instance, assume that the bus stops involved in the transfer between routes A and B are nearly 100-m apart. A null waiting time would make it impossible to perform this transfer.

The real transfer represents each feasible transfer as detected in the real service execution. The same definition of *simultaneous* arrivals is adopted, but the analysis of the real AVL data is performed.

Next, an acceptable threshold (e.g., 80%) is set to evaluate the successfulness of a scheduled transfer against the candidate one and a real transfer against the scheduled one. This threshold takes into account recent quality norms [39], [40]. Figure 2 shows that if target thresholds are not met, a separate analysis on routes may help 1) revise the original schedule or 2) perform a diagnosis on the sources of unreliability, which arise because of insufficient punctuality or regularity measurements [52], [61].

In case 1), a time offset is added to the schedule to plan a successful transfer. In case 2), it is crucial to identify the dominant source that results in the observed causes. It is worth noting that unreliability sources may be generated by several causes because many factors may be correlated with each other [38]. In this framework, we classify unreliability sources as follows: 1) improper service design (ISD), 2) driver and/or supervisor failures (D&SFs), 3) uncertainties in passenger volumes (UPVs), and 4) uncontrollable external factors (UEFs). Each source is linked to a list of related components (e.g., UPV is computed from the time spent and has these components: lower (L)-UPV, upper (U)-UPV, and OK). Next, we detect the component that has a relative frequency larger than 50% in each time period and bus stop to recognize the dominant source that results in the observed causes and point out where major attention is needed. The crossed reading of the dominant components of each source provides knowledge of the most relevant unreliability problems and their connections to the causes for each bus stop and period. The overall notation is summarized in "Summary of Notational Glossary."

AVL Data Preprocessing

Consider any two routes A and B (as well as their scheduled departure headways). They could be selected according to the demand transfers if some tools are adopted to detect passenger volumes. However, in this framework, only AVL data are available, and the routes are selected when at least one bus stop is shared. Moreover, the investigation of all the pairs of routes at transfer bus stops contributes to the applicability of the framework.

For each route, pick up their archived AVL data from a database on the provided service. The main attributes of the AVL data returned by a standard architecture are date, vehicle block (i.e., a number representing the vehicle shift), route direction, trip number, bus stop code and order, and the actual and scheduled arrival or departure times. Finally, the time spent or the dwell time in a predefined area around each bus stop is retrieved (this step depends on the specific AVL architecture).

A comparison of the overall number of actual and scheduled bus arrivals (or departures) may show a lack of data for each route. Thus, if AVL data are not supposed to sufficiently represent the service, one may adopt an optional a priori data validation, which looks to accept or reject AVL data related to every day in a month. Some numerical examples of data validation are shown in [35].

Next, for each route, because AVL data are not ready for use as they are, the framework performs the proper handling

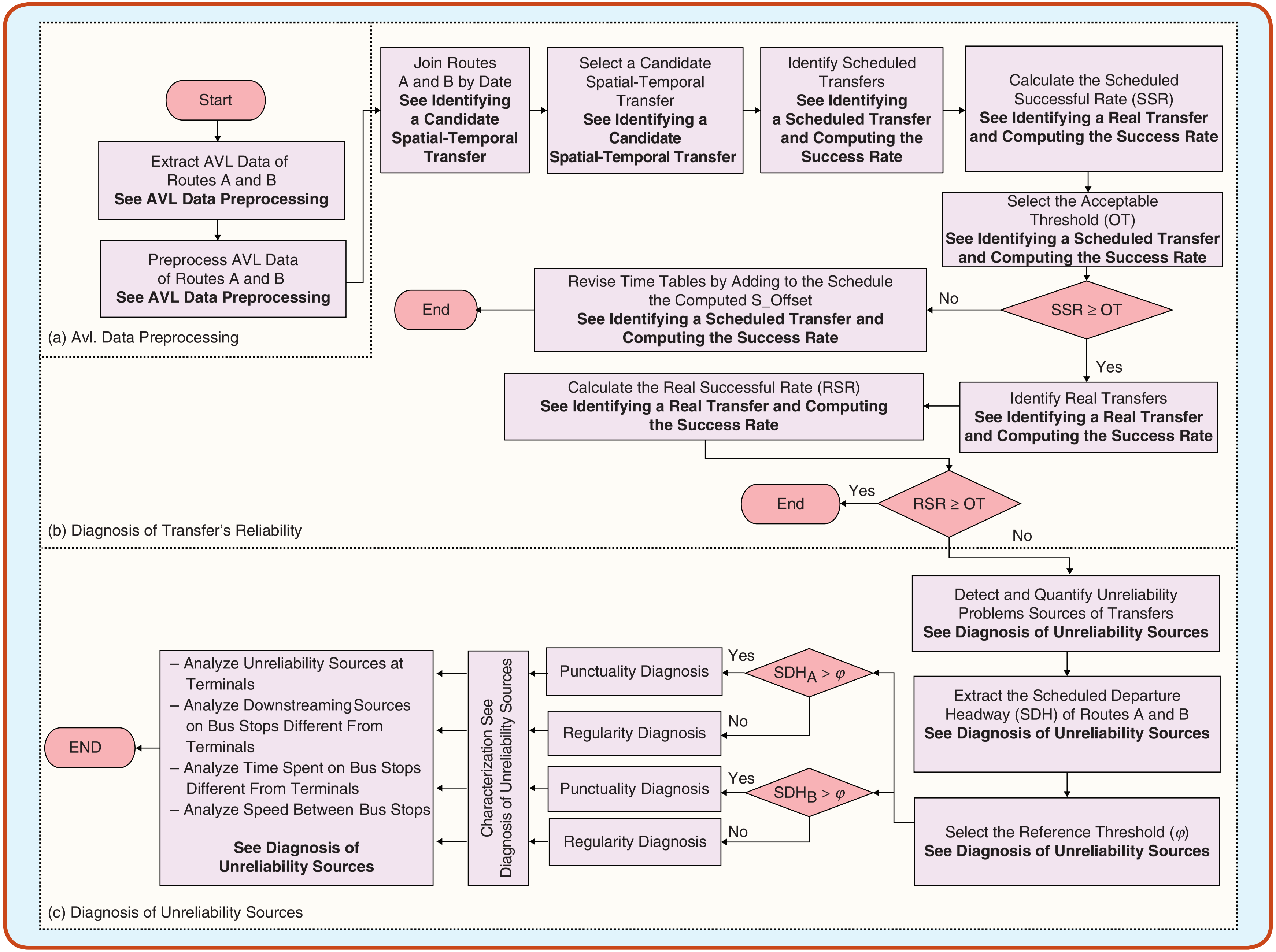


FIG 2 The framework for the analysis of transfer reliability. OT: objective threshold.

of possible anomalies to account for BO and distinguishes from among the missing data points (i.e., the TF or IOS) [35]–[37], [52], [61].

More precisely, two procedures address BO and missing data points, respectively. If passengers board on the first arriving bus (i.e., no pass up), BO is observed as follows. First, the actual arrival (or departure) times are chronologically ordered to account for the real bus arrivals at bus stops because passengers are not interested in the right schedule of buses. Second, scheduled arrival (or departure) times are chronologically ordered to account for published timetables. Third, the lists returned by the previous orders are joined.

The missing data points are recognized by building a monthly report of IOSs, which is merged with the original schedule and then with the AVL data. In this method, any missing data is considered a TF unless it is a reported as an IOS.

As a result, two different ordered lists, $\mathrm{M_X}^{\mathrm{A}}$ and $\mathrm{M_X}^{\mathrm{B}}$, of processed AVL data are returned for routes A and B, respectively. Some numerical examples of AVL data preprocessing are shown in [35] and [52].

Diagnosis of a Transfer's Reliability

Identifying a Candidate Spatial-Temporal Transfer

Let

- d be the date (or the pair-data time to account for shifts overlapping for two consecutive days)
- I and J be the sets of all bus stops for routes A and B, respectively
- H and K be the sets of runs for routes A and B, respectively
- W be the set of candidate transfers (i.e., possible, in terms of space and time)
- X^A_i, Y^A_i, and X^B_j, Y^B_j be the coordinates of bus stops $i \in I$ and $j \in J$ for routes A and B, respectively
- $SAT^{\mathrm{A}}{}_{ihd}$,(or $SDT^{A}{}_{ihd}$) be the scheduled arrival (or departure) time of run $h \in H$ of route A at bus stop $i \in I$ on date d
- $RAT^{A}{}_{ihd}$ (or $RDT^{A}{}_{ihd}$) be the real arrival (or departure) time of run $h \in H$ of route A at bus stop $i \in I$ on date d
- $SAT^{\mathrm{B}}{}_{jkd}$,(or $SDT^{B}{}_{jkd}$) be the scheduled arrival (or departure) time of run $k \in K$ of route B at bus stop $j \in J$ on date d
- $RAT^{B}{}_{jkd}$ (or $RDT^{B}{}_{jkd}$) be the real arrival (or departure) time of run $k \in K$ of route B at bus stop $j \in J$ on date d
- $rts^{A}{}_{ihd}$ and $rts^{B}{}_{jkd}$ be the real times spent by runs $h \in H$ and $k \in K$ at bus stops $i \in I$ and $j \in J$, respectively, on date d
- $\mathrm{M_X}^{\mathrm{A}}$ and $\mathrm{M_X}^{\mathrm{B}}$ be the ordered lists of records returned by stage A) for routes A and B, respectively
- $SDH^{At}{}_{i(h,h\text{-}1)}$ be the scheduled departure headway at bus stop $i \in I$ between runs $h \in H$ and $h-1 \in H$ of route A at time period t
- $SDH^{B,t}{}_{j(k,k\text{-}1)}$ be the scheduled departure headway at bus stop $j \in J$ between runs $k \in K$ and $k-1 \in K$ of route B at time period t.

The relevant attributes of each record in $\mathrm{M_X}^{\mathrm{A}}$ are d, route, vehicle block, run $h \in H$, bus stop $i \in I$ (the code and the order in the route), bus stop location (the X_i and Y_j coordinates, if appropriate), route direction, $SAT^{\mathrm{A}}{}_{ihd}$, (or $SDT^{\mathrm{A}}{}_{ihd}$), $RAT^{\mathrm{A}}{}_{ihd}$ (or $RDT^{\mathrm{A}}{}_{ihd}$), and $rts^{\mathrm{A}}{}_{ihd}$ by run $h \in H$ at bus stop $i \in I$.

The relevant attributes of each record in $\mathrm{M_X}^{\mathrm{B}}$ are date d, route, vehicle block, run $k \in K$, bus stop $j \in J$ (the code and the order in the route), bus stop location (the X_j and Y_j coordinates, if appropriate), route direction, $SAT^{\mathrm{B}}{}_{jkd}$, (or $SDT^{\mathrm{B}}{}_{jkd}$), $RAT^{\mathrm{B}}{}_{jkd}$ (or RDT_{Bjkd}), and $rts^{\mathrm{B}}{}_{jkd}$ by run $k \in K$ at bus stop $j \in J$.

In the analysis of $\mathrm{M_X}^{\mathrm{A}}$ and $\mathrm{M_X}^{\mathrm{B}}$, the first task is to join the records from routes A and B based on d. Next, a search of shared and unshared bus stops in the space and time domains is performed as follows. By the coordinates and the scheduled departure and arrival times at bus stop $i \in I$ on route A of a record in $\mathrm{M_X}^{\mathrm{A}}$ and the coordinates and scheduled departure and arrival times at bus stop $j \in J$ on route B of a record in $\mathrm{M_X}^{\mathrm{B}}$, this search can be performed using an algorithm denoted as identify a candidate transfer (ICT).

First, for each date d, ICT extracts each record in $\mathrm{M_X}^{\mathrm{A}}$, which is joined to each record in $\mathrm{M_X}^{\mathrm{B}}$. Next, ICT creates for each record in $\mathrm{M_X}^{\mathrm{A}}$ a spatial circular boundary of radius δ, which reflects the maximum acceptable walking distance between two bus stops. Clearly, if $\delta = 0$, bus stops are shared. Moreover, ICT creates temporal boundaries of length $SDH^{At}{}_{i(h,h\text{-}1)}$ and $SDH^{B,t}{}_{j(k,k\text{-}1)}$, respectively, that reflect the maximum transfer time to make a transfer from route A (or B) to route B (or A) for each time period. Although one may alternatively adopt the percentiles of the waiting times, the maximum transfer times are consistent with the assumption about a superior limit on waiting times so that the longest waiting time does not exceed the maximum headway for the pair of routes involved in a transfer. Moreover, setting a maximum value of waiting time is also beneficial in the case of unshared bus stops as they increase the opportunities to make a transfer.

Second, ICT computes the geographical or Euclidean distance—depending on the coordinates in use—between bus stops $i \in I$ and $j \in J$ and denotes this value by dist_{ij}. It is assumed that passengers know the pedestrian paths shorter than δ to access the unshared bus stops. In the case of the Euclidean distance, dist_{ij} is computed as

$$\mathrm{dist}_{ij} = \sqrt{(X_i - X_j)^2 + (Y_i - Y_j)^2}\ \forall\ i \in I;\ \forall j \in J. \tag{1}$$

Third, ICT computes the temporal length between bus stops $i \in I$ and $j \in J$ and denotes them by time_{ij} and time_{ji}, respectively. More precisely, these times are computed as

Summary of Notational Glossary

AVL: automatic vehicle location
BO: bus overtaking
D&SF: driver and/or supervisor failure
IOS: incorrect operation in service
ISD: improper service design
LoS: level of service
OT: objective threshold
TF: technical failure
UEF: uncontrollable external factors
UPV: uncertainties in passenger volumes.

The overall notation is presented in Table S1.

Table S1. The notational glossary.

Symbol	Description	Units
I	Set of all bus stops on route A	—
J	Set of all bus stops on route B	—
H	Set of runs on route A	—
K	Set of runs on route B	—
W	Set of candidate transfers	—
S	Set of scheduled transfers	—
R	Set of real transfers	—
i	Bus stop index on route A	—
j	Bus stop index on route B	—
h	Run index on route A	—
k	Run index on route B	—
w	Candidate transfers	—
s	Scheduled transfers	—
r	Real transfers	—
RDT_{ih}^{A}	Real departure time at bus stop $i \in I$ for run $h \in H$ on A	hh:mm:ss
RAT_{ih}^{A}	Real arrival time at bus stop $i \in I$ for run $h \in H$ on A	hh:mm:ss
SAT_{ih}^{A}	Scheduled arrival time at bus stop $i \in I$ for run $h \in H$ on A	hh:mm:ss
SDT_{ih}^{A}	Scheduled departure time at bus stop $i \in I$ for run $h \in H$ on A	hh:mm:ss
RDT_{jk}^{B}	Real departure time at bus stop $j \in J$ for run $k \in K$ on B	hh:mm:ss
RAT_{jk}^{B}	Real arrival time at bus stop $j \in J$ for run $k \in K$ on B	hh:mm:ss
SAT_{jk}^{B}	Scheduled arrival time at bus stop $j \in J$ for run $k \in K$ on B	hh:mm:ss
SDT_{jk}^{B}	Scheduled departure time at bus stop $j \in J$ for run $k \in K$ on B	hh:mm:ss
$SDH_{i(h,h-1)}^{A}$	Scheduled departure headway at bus stop $i \in I$ between runs $h \in H$ and $h-1 \in H$ on A	hh:mm:ss
$SDH_{j(k,k-1)}^{B}$	Scheduled departure headway at bus stop $j \in J$ between runs $k \in K$ and $k-1 \in K$ on B	hh:mm:ss
rts_{ih}^{A}	Real time spent by run $h \in H$ at stop $i \in I$	s
rts_{jk}^{B}	Real time spent by run $k \in K$ at stop $j \in J$	s
TT	Candidate transfers	#
S_Offset_{ij}	Scheduled time offset between the scheduled earlier departures and the latest arrivals of at bus stops $i \in I$ and $j \in J$ for run $h \in H$ on A and run $k \in K$ on B	s
ST_{ij}	Scheduled transfer	#
SSTs	Scheduled successful transfers	#
SSR_{ij}^{t}	Scheduled successful rate	%
R_Offset_{ij}	Real-time offset between the scheduled earlier departures and the latest arrivals at bus stops $i \in I$ and $j \in J$ for run $h \in H$ on A and run $k \in K$ on B	s
RT_{ij}	Real transfer	#
RSTs	Real successful transfers	#
RSR_{ij}^{t}	Real successful rate	%
OT	Objective threshold	%
v_p	Pedestrian speed which is set 4 km/h, according to [68]	m/s
δ	Maximum acceptable walking distance, which is set at 400 m, according to ([65]–[67])	m
φ	Threshold that distinguishes from high- and low-frequency services	min
$dist_{ij}$	Distance between bus stops $\mathrm{i} \in \mathrm{I}$ on route A and $\mathrm{j} \in \mathrm{J}$ on route B	m
$time_{ij}^{AB}$	Time length between the scheduled departure time of route B and the scheduled arrival time of route A	s
$time_{ji}^{BA}$	Time length between the scheduled departure time of route A and the scheduled arrival time of route B	s

$$\mathrm{time}_{ij} = (SDT_{jkd}^{B} - SAT_{ihd}^{A}) \qquad \forall\ i\ \in I;\ \forall j\ \in J, \qquad (2)$$

$$\mathrm{time}_{ji} = (SDT_{ihd}^{A} - SAT_{jkd}^{B}) \qquad \forall\ i\ \in I;\ \forall j\ \in J. \qquad (3)$$

Equations (2) and (3) represent the time lengths between the scheduled departure time of route B (or A) and the scheduled arrival time of route A (or B). These equations reflect the time interval needed to make a (potential) transfer from route A (or B) to route B (or A).

Then, for each pair of records in MX^{A} and MX^{B}, a candidate transfer is denoted as $w_{ij} \in W$ and identified as

$$w_{ij} = \begin{cases} 1 \text{ if } \begin{cases} 0 \le \text{dist}_{ij} \le \delta \quad \forall\, i \in I;\ \forall\, j \in J & (4.1) \\ \text{and} \\ 0 \le \text{time}_{ij} \le SHD^{B,t}_{j(k,k-1)}\ \forall\, i \in I; \forall j \in J & (4.2) \\ \text{and} \\ 0 \le \text{time}_{ji} \le SHD^{A,t}_{i(h,h-1)}\ \forall\, i \in I; \forall j \in J & (4.3) \end{cases} \\ \\ \text{else } 0. \end{cases} \tag{4}$$

Note that w_{ij} denotes a transfer both from bus stop $i \in I$ to bus stop $j \in J$ and vice versa.

Equation (4.1) shows that in a successful spatial transfer between routes A and B, the bus stops should be shared (i.e., $dist_{ij} = 0$) or located at an acceptable walking distance, which is set at the upper limit as δ. Equations (4.2) and (4.3) show that in a successful temporal transfer, a maximum waiting time is included. This time depends on the scheduled headways of the routes at hand because passengers may use this time to reach a quasi-shared bus stop and have a short waiting time before boarding. Clearly, both (4.2) and (4.3) are required to guarantee a full transfer (i.e., from route A to B and vice versa). Next, the list of all the possible candidate transfers is rearranged in order of increasing dates, bus stop numbers,dist_{ij}, time_{ij}, and time_{ji}. A new array denoted as PT is generated to save the list of candidate transfers. Finally, the total number of all the records in the PT is computed, and it is denoted as *TT*. More formally,

$$TT = \sum_{i \in I} \sum_{j \in J} w_{ij}. \tag{5}$$

Identifying a Scheduled Transfer and Computing the Success Rate

Once each candidate transfer $w_{ij} \in W$ is identified, the method switches first to the identification of a scheduled transfer and next to the identification of the success rate. These steps are performed by an algorithm denoted as identify and compute scheduled transfer (ICST).

To begin, for each w_{ij}^{th} of PT, ICST computes the following quantities starting from the walking time (between these bus stops), which is denoted as $Walking\_time_{ij}$. More formally, let v_p be the pedestrian speed.

$$Walking\_time_{ij} = \frac{\text{dist}_{ij}}{v_p} \qquad \forall\, i \in I;\ \forall j \in J. \tag{6}$$

Equation (6) includes the case of unshared (but reasonably close) bus stops. If the bus stops are shared, (6) returns to zero.

Second, ICST considers the scheduled arrival and departure times of routes A and B, respectively. Next, it computes the latest arrival and the earliest departure, which are denoted as S_A_{ij} and S_D_{ij}, respectively. More formally,

$$S\_A_{ij} = \max\ (SAT^{A}_{ihd};\ SAT^{B}_{jkd}) \forall\, i \in I;\ \forall j \in J, \tag{7}$$

$$S\_D_{ij} = \min\ (SDT^{A}_{ihd};\ SDT^{B}_{jkd})\ \forall\, i \in I;\ \forall j \in J. \tag{8}$$

Equations (7) and (8) return the data input for the calculation of the scheduled time offset, which makes the transfer between route A and B possible and vice versa. For instance, if route A arrives and departs before the arrival of route B, the passengers of route A can board on route B, but the contrary is not possible. Therefore, we can compute the scheduled time offset, which is denoted as S_Offset_{ij}, as

$$S\_Offset_{ij} = (S\_D_{ij} - S\_A_{ij}) \qquad \forall\, i \in I;\ \forall j \in J. \tag{9}$$

Equation (9) shows that, if $S\_Offset_{ij} > 0$, the passengers may perform a transfer from route A to B and vice versa (at least at shared bus stops). Conversely, a negative S_Offset_{ij} represents the minimal time required to compensate for the missed transfer; this time should be added to the original schedule to make a transfer possible. Third, ICST checks whether or not a scheduled transfer may be performed by comparing the scheduled time offset with the walking time and the maximum of the scheduled headways of routes A and B, respectively. More precisely, let ST_{ij} be the scheduled transfer; it can be computed as

$$ST_{ij} = \begin{cases} 1 \text{ if } \left(\begin{array}{l} Walk\ time_{ij} \le S\_Offset_{ij} \\ \qquad \le \text{Max}(SDH^{At}_{i(h,h-1)}; SDH^{Bt}_{i(k,k-1)}) \end{array} \right) \\ \\ \forall\, i \in I;\ \forall j \in J;\ \forall\, h \in H;\ \forall k \in K \\ \\ \text{else } 0. \end{cases} \tag{10}$$

Equation (10) helps determine whether a candidate transfer between $i \in I$ and $j \in J$ is a successful scheduled transfer according to S_Offset_{ij}. More precisely, the first part of (10) shows that S_Offset_{ij} must be larger or equal to that of $Walk\ time_{ij}$. This situation typically occurs when bus stop $i \in I$ and bus stop $j \in J$ are quasishared because passengers need to walk from the arrival bus stop toward the departure one. The last part of (10) sets a maximum of S_Offset_{ij} to make the transfer feasible within a time interval. This interval is set as the maximum between the time headways of routes A and B. We assume that the arrivals of vehicles do not exceed a tolerable waiting time, which reflects the worst-possible operating conditions (i.e., the service is irregular). This time includes walking and waiting time in the case of unshared bus stops, or only waiting time in the case of shared bus stops. In the last case, (10) reduces to

$$0 \le S\_Offset_{ij} \le \text{Max}(SDH^{At}_{i(h,h-1)}; SDH^{Bt}_{i(k,k-1)}). \tag{11}$$

It is worth noting that (10) reflects situations of real life. For instance, consider two unshared bus stops: passengers alighting from route A at bus stop $i \in I$ should cross the street to board route B at bus stop $j \in J$ and vice versa. The inequality $S\_Offset_{ij} \geq \mathrm{time}_{ij}$ guarantees that passengers will walk from bus stop $i \in I$ to bus stop $j \in J$ and vice versa. Moreover, setting the $S\_Offset_{ij} \leq \mathrm{Max}$ of headways helps passengers to have a tolerable waiting time at bus stops $i \in I$ and $j \in J$, respectively. Clearly, the setting of the maximum headways may also include the walking time needed to reach the departure bus stop from the arrival one.

Next, when each scheduled transfer is marked as success or fail, ICST computes the total number of scheduled successful transfers (*SST*s):

$$SST = \sum_{i \in I} \sum_{j \in J} ST_{ij}. \tag{12}$$

Then, a new step computes the rate of success for each bus stop (shared and unshared). This is done to determine whether a candidate transfer results in an *SST*. This success rate is the contribution of each shared (and unshared) bus stop to the successful candidate transfer between routes A and B. To perform this task, the scheduled successful rate, denoted as SSR^{t}_{ij}, is computed by the percentage ratio between (12) and (5) for each time period *t*. More formally,

$$SSR^{t}_{ij} = 100 * \frac{SST}{TT} \qquad \forall\, i \in I;\ \forall j \in J. \tag{13}$$

Finally, the last step shows where attention is needed to correct the unreliability of transfers. This task is performed by establishing an objective threshold (OT) for the acceptability of SSR^{t}_{ij}. If this threshold is not met, some actions will be required to correct transfer reliability. More precisely, this step works according to the following rules:

- If $SSR^{t}_{ij} < \mathrm{OT}$, the PTC is strongly recommended to revise the timetables of routes A or B by adding computed S_Offset_{ij} to the schedule until the desired OT is reached. Next, the overall method stops.
- If $SSR^{t}_{ij} \geq \mathrm{OT}$, the algorithm ICST shifts to the analysis of the real transfer, as presented in the following section.

Identifying a Real Transfer and Computing the Success Rate

It is worth noting that the aim of this research is to analyze simultaneous arrivals at shared and unshared bus stops. Therefore, our analysis includes both early and late arrivals, which can be acceptable in the case of bidirectional transfers (i.e., from A to B and vice versa); this is because AVL raw data are preprocessed to reflect the sequence of arrivals received by passengers for real.

Once $SSR^{t}_{ij} \geq \mathrm{OT}$, the method switches first to the identification of a real transfer and next to the identification of its success rate. These steps are performed by the identify and compute real transfer (ICRT) algorithm.

First, ICRT considers the real arrival and departure times of routes A and B, respectively. Next, it computes the latest arrival and the earliest departure, which are denoted as R_A_{ij} and R_D_{ij}, respectively. The resulting equations are

$$R\_A_{ij} = \max\,(RAT^{A}{}_{ihd};\, RAT^{B}{}_{jkd}) \qquad \forall\, i \in I;\ \forall j \in J, \tag{14}$$

$$R\_D_{ij} = \min\,(RAT^{A}{}_{ihd};\, RAT^{B}{}_{jkd}) \qquad \forall\, i \in I;\ \forall j \in J. \tag{15}$$

Equations (14) and (15) return the data input for the calculation of the real-time offset that makes the transfer between route A and B possible, and vice versa. This real-time offset is denoted as R_Offset_{ij}, and it is computed as

$$R\_Offset_{ij} = (R\_D^{BA}{}_{ij} - R\_A^{BA}{}_{ij}) \qquad \forall\, i \in I;\ \forall j \in J. \tag{16}$$

Second, ICRT checks whether or not a real transfer may be performed. This is done by comparing the real offset time with the walking time as well as the maximum of the real headways of routes A and B, as computed by (6), respectively. More precisely, let RT_{ij} be the real transfer; it is possible to formulate the real transfer as

$$RT_{ij} = \begin{cases} 1 \text{ if } \left(\begin{array}{l} Walk\ time_{ij} \leq R\_Offset_{ij} \leq \\ \quad \leq \mathrm{Max}(RDH^{At}_{i(h,h-1)}; RDH^{Bt}_{i(h,h-1)}) \end{array} \right) \\ \qquad\qquad \text{else } 0. \end{cases} \tag{17}$$

Third, when each real transfer is marked as success or fail, ICRT computes the total number of real successful transfers (*RST*s):

$$RST = \sum_{i \in I} \sum_{j \in J} RT_{ij}. \tag{18}$$

Fourth, the rate of success of real transfers is computed for each bus stop to determine whether a real transfer results in an *SST*. To perform this task, the real successful rate, denoted as RST^{t}_{ij}, is computed by the percentage ratio between (18) and (5) for each time period *t*. More formally,

$$RSR^{t}{}_{ij} = 100 * \frac{RST}{SST} \qquad \forall\, i \in I;\ \forall j \in J. \tag{19}$$

Finally, the computed RSR^{t}_{ij} is compared with the OT to show if and where attention is needed to correct the unreliability of real transfers. More precisely, this action works as follows.

- If $RSR^{t}_{ij} \geq \mathrm{OT}$, the overall method ends because the transfers are well planned and delivered; thus, no corrective action is required.

- If $RSR^t_{ij} < \mathrm{OT}$, the PTC is strongly advised to detect and quantify unreliability problem sources of transfers, as detailed in the following section.

Diagnosis of Unreliability Sources

The detection and quantification of unreliability problem sources of transfers may be performed by the diagnosis of the regularity and/or punctuality of each route. To perform this diagnosis, routes A and B are classified according to their scheduled headways, which may be shorter or longer than a selected threshold, denoted as φ. Next, for routes having headways shorter than φ, a regularity diagnosis is run. Conversely, the punctuality is analyzed.

Both analyses start with the characterization of the performance in terms of regularity or punctuality. Next, the most common unreliability sources are evaluated. More precisely, in the case of regularity measurements, one computes the actual and scheduled headways as the difference between two consecutive arrival (or departure) times and accounts for TFs and IOSs as follows. TFs are not used to compute the real headways because no information on real arrivals (or departures) is available. On the contrary, IOSs are used to compute the real headways because these temporal gaps are experienced by passengers. Next, to show which segments of the route do not exhibit a sufficient regularity level, the coefficient of the variation of headway (C_{vh}) is computed for the interested bus stops and time periods. According to [35] and [52], the C_{vh} is chosen as it is objective, penalizes longer waiting times (the input is 100% customer oriented), does not require particular applicability conditions, and can help detect which parts of the transit route may be affected by bus bunching. The C_{vh} is linked to a predefined level of service (LoS) [53]. Moreover, in this article, the bunching represents an effect of irregularity instead of a cause of irregularity, which affects transfer reliability and may depend on speed, traffic congestion, passenger volumes, and so on [38].

In the case of punctuality measurements, deviations are computed from the original schedule as the difference between the actual and scheduled arrival (or departure) times and accounts for TFs and IOSs as follows. TFs are disregarded as they refer to technical problems instead of operations in the service. IOSs are penalized because passengers are actually conditioned by these missing bus arrivals (or departures). Next, the percentage of punctual buses is computed for the interested bus stops and time periods and can be linked to an appropriate LoS [53]. In both cases, if the LoS reports an insufficient mark, denoted as D; E; or F; the service needs further investigation to understand the possible irregularity sources. All the details of these analyses are reported in [35], [36], and [52].

Once the worst LoS is determined, the analysis of unreliability sources follows. Our analysis considers current bus stops $i \in I$ and $j \in J$, previous ones $i-1 \in I$ and $j-1 \in J$, and the leg between them. The recognition of unreliability sources is performed by a proper analysis on the deviation from a planned attribute, which can be extracted from massaged AVL data. It includes 1) an analysis of sources at the terminals (i.e., headway deviation and/or schedule deviation versus the available recovery time), 2) an analysis of downstreaming sources on bus stops that are different from those at the terminals (i.e., headway and/or schedule deviations along the route), 3) an analysis of the time spent at bus stops that is different from the time spent at terminals to emphasize problem sources due to passenger volumes (i.e., headway and schedule deviation on the time spent or the dwell time), and 4) an analysis of the speed between bus stops to emphasize the problem sources that are different from passenger volumes (e.g., ISD). All the details of these analyses are reported in [37] and [38].

Finally, it is worth noting that sometimes passengers may not transfer due to unexpected events. For instance, some riders take route A and want to switch to take B-1 bus at a stop, but they miss the scheduled B-1 bus and are reluctant to wait for the next bus, choosing instead to walk or take taxis. To account for these cases, one would need to track passengers (at least at bus stops) to detect such choices, but this technological level is unavailable in this research. To our knowledge, this situation is quite common in some (perhaps less-advanced) PTCs due to both less-advanced infrastructures and data privacy issues. Moreover, the impossibility of tracking passengers does not allow to detect passengers adopting pass-up strategies (i.e., passengers are supposed to board on the first arriving vehicle; therefore, we cannot do more with AVL data only). Accordingly, these cases result in an interesting research perspective for when tracking opportunities will be available.

Real Case Experiment

Context

This framework has been experimented with in Cagliari, a city of fewer than one-half million inhabitants on the island of Sardinia (Italy). The local public transport company is CTM, and it is in charge of public transportation. It uses 271 vehicles (i.e., buses and trolleys) and makes approximately 40.8 million trips a year. Moreover, these vehicles travel more than 12.4 million km per year along 34 routes [62].

For the sake of synthesis, the proposed method is tested on frequency-based routes. A threshold (i.e., φ) of 10–12 min of scheduled headways is set to separate shorter and longer headways (or high- and low-frequency routes) [50], [53], [63]. CTM's policies have not yet implemented shared bus stops to improve its system's reliability. Nevertheless, the improvement of the system's reliability using shared bus stops in space and time domains is relevant. Because our goal is to analyze simultaneous arrivals as defined in the "Methodological Framework" section, this analysis includes both early and late arrivals, which can also be acceptable in the case of unidirectional transfers.

The proposed method was tested on two different routes with both shared and unshared bus stops. These routes include transfers that serve important points in the city and share some corridors due to infrastructural characteristics. They were selected for the experimentation of this framework (and not for the optimal location of bus stops). According to bus drivers' and passengers' claims, low reliability occurred in several parts of these routes, which may affect the transfers at some bus stops, but the PTC was not able to confirm this perception. Therefore, it was motivated to evaluate the transfer reliability for these routes. Moreover, they present the following characteristics.

The first route (denoted as A) is a suburban line connecting the city's center to the north area. It travels in the northbound direction for roughly 19.5 km with 49 bus stops and in the westbound direction for approximately 20.94 km with 46 bus stops. The bus stops for the experimentation on route A are represented in Figure 3: the northbound direction is shown in blue and the westbound in red. This route can be divided into four parts, corresponding to different municipalities. The numbers in Figure 3 denote bus stops. During peak hours, the service is provided with high-load-capacity vehicles (18 m 140 passengers) to meet the demand of university students. The headway is 17 min, on average, from 5:00 to 23:00.

The second route (denoted as B) moves in the eastbound direction for roughly 8.5 km with 11 bus stops and in the westbound direction for approximately 8.7 km with 12 bus stops. The experimentation on route B concerns the final part of the westbound direction, which is depicted with continuous green lines in Figure 3. The terminal of the westbound direction is bus stop 12, and the eastbound direction is denoted as discontinuous lines. This route can be divided into two parts: the first part runs on an extra urban road, the second part moves along two-way streets in the city in mixed-traffic conditions (e.g., with vehicles looking for parking and pedestrian flows.) Its headway is 15 min from 7:00 to 21:00. The vehicles in this route have the same typology, capacity (105 passengers), length (12 m), and low floors.

As displayed in Figure 3, the southbound direction of route A shares the same bus stop with the westbound direction of route B. This bus stop is coded as number 36 for route A and as number 10 for route B. The northbound direction of route A shares the same bus stop with the westbound of route B. This bus stop is coded as number 13 for route A and as number 12 for route B. Moreover, all the bus stops shown in Figure 3 are located within an acceptable walking distance.

Experimental Setup and Results

Since 2007, all of the buses have been equipped with a specific AVL architecture, which mainly records the actual and scheduled arrival times, measured in minutes and seconds at each bus stop [64]. Approximately 100,000 AVL data records are available daily over the overall network. In addition, control room operators follow buses in real time at the dispatch center and inform drivers of real-time tactics to improve system reliability. As a vehicle terminates its service, it moves back to the depot where the data recorded during the daily shift are downloaded by a wireless connection. Daily AVL data are stored in a central database.

Arrival time data are processed for practical reasons because only arrival times are typically provided in bus schedules. Moreover, most buses have low floors and specialized doors to speed up boarding and alighting operations. Hence, arrival times can well approximate when passengers board buses and when trips are supposed to start.

In this analysis, AVL data were collected from 7:00 to 20:59, but we focused on only the interval from 13:00 to 19:59 for the sake of simplicity. The AVL data of these routes were collected during weekdays in March 2019.

The framework in the "Methodological Framework" section was developed and implemented on Microsoft Access and Microsoft Excel running on a standard PC. At the time of the analysis, this methodology has not yet been implemented in a single tool, but the executions of parts A, B, and C were nearly automatic, and they were performed in an acceptable time.

According to stage A) of the "Methodological Framework" section, BO is addressed by ordering data according to actual transit times. Using the AVL database of CTM, the gaps due to a TF were detected and processed, whereas in this specific experimentation, the IOSs were neglected due to their very small number. At the end of stage A), we processed 144,853 AVL records: 119,678 and 25,175 for routes A and B, respectively.

Next, the framework was implemented, as shown in stage B) of the "Methodological Framework" section. For this experiment, δ was set at 400 m [65]–[67]. This value of δ is larger than the distances between the bus stops in Figure 3.

According to part B 1), for each pair of $i \in I$ and $j \in J$, we identified each candidate transfer w_{ij} to check whether or not it was successfully performed. Next, according to (5), we computed the total number of candidate transfers (i.e., the TT) and identified 712 candidates.

According to part B 2), we set $v_p = 4$ km/h [68] and computed the number of scheduled transfers according to (6)–(12). A total of 111 successful scheduled transfers is re-

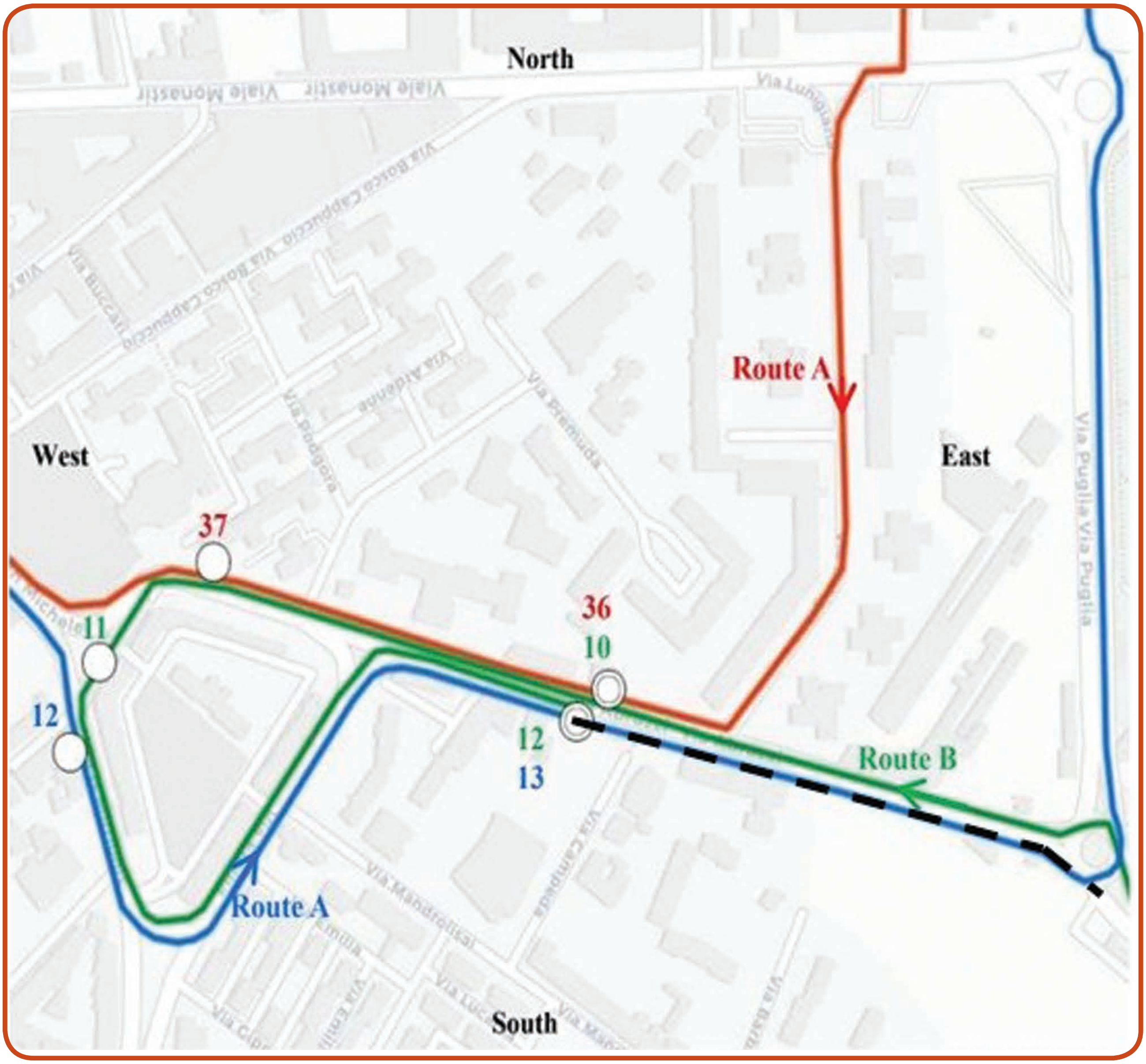


FIG 3 An overview of the bus stops of interest for routes A and B.

ported. Thus, the overall rate of success is 15.59%, which is quite a low percentage. Next, the scheduled successful rate (i.e., SSR^{t}_{ij}) was computed by (13) for each time period and pair of bus stops. This outcome is represented in the control dashboard of Figure 4, where columns one and three represent the route of interest, whereas columns two and four report the bus stops involved in the transfer. Columns five through 11 represent the time periods. Each entry included in the columns represents the success rate of a transfer between routes A and B.

Figure 4 clearly shows that 1) the candidate transfers were not available at several bus stops for each time period (the entries of these data are blank) and 2) most of the candidate transfers were not made. Only a small percentage of transfers were successfully implemented on unshared bus stops (i.e., 10 and 13) in the time period between 13:00 and 13:59 and shared bus stops (i.e., 10 and 36) in two time periods (i.e., 17:00–17.59 and 19:00–19:59). Moreover, Figure 4 confirms that a standard *modus operandi* is adopted by this PTC as it aims to determine the dispatching times of each route in isolation [26], because only very few entries are different from 0%. Thus, transfers are usually not scheduled; however, long waiting times are not desirable. Thus, PTCs may apply control strategies to make some adjustments.

Next, if the OT is set at 80% [39], [40], the case of $SSR^{t}_{ij} <$ OT is observed in most of the cases, and the PTC

				Time Period						
Route	Bus Stop	Route	Bus Stop	13 13.59	14 14.59	15 15.59	16 16.59	17 17.59	18 18.59	19 19.59
A	12	B	10							
A	12	B	11		0%	0%				
A	12	B	12	0%			0%		0%	
A	13	B	10	**100%**						
A	13	B	12							
A	36	B	10					**100%**		**100%**
A	36	B	11					0%		
A	36	B	12		0%	0%				
A	37	B	10			0%				
A	37	B	11					0%		0%
A	37	B	12	0%			0%			

FIG 4 The scheduled success rates of routes A and B for the considered time periods.

should correct offsets when and where the former inequality holds. In the experimentation, we set the time offset up to 120 s and the total number of transfers needing revision to 601. The PTC may synchronize roughly 50% of transfers, which would be especially beneficial for unshared bus stops (Table 1).

In the "lucky" cases of $SSR^t_{ij} \geq$ the OT, the identification of real transfers and the computation of the real success rate (RSR) was performed according to part B 3) of the "Methodological Framework" section. More precisely, only 51 successful real transfers were observed according to (14)–(18). Thus, the overall RSR is 45.95%, which is quite low as well. Next, the successful rate for the real transfer (i.e., RSR_{ij}) was computed for each time period and pair of bus stops by (19). The outcomes are reported in the control dashboard of Figure 5, which is organized as Figure 4 (for the sake of consistency, we retained the null entries in Figure 5).

Figure 5 shows that most of the scheduled transfers were not made. Only a very small percentage of transfers was implemented. Interestingly, the large values of RSR_{ij} were provided between unshared bus stop 13 of route A and the unshared bus stop 10 of route B. Moreover, Figure 5 depicts another unexpected result regarding the entries reported in red: They represent the real successful rate, which was computed by dividing the number of RSTs by the number of candidate transfers for each time period. Our analysis includes both early and late arrivals, which may help finalize a candidate transfer. More precisely, our framework presents cases in which a scheduled transfer is not planned (e.g., from A-12 to B-11 at time periods 14:00–14:59 and 15:00–15:59 equals 0%) but the real transfer occurred (e.g., from A-12 to B-11 at time periods 14:00–14:59 and 15:00–15:59 equals 6%) even if for a small percentage. This analysis provides further evidence that the PTC tries to synchronize transfers by applying control strategies.

For bus stops with $RSR_{ij} > 0$, one observes that $RSR_{ij} <$ the OT; hence, part C) of the "Methodological Framework" section must be run to perform a diagnosis of unreliability sources of missed transfers. To carry out this diagnosis, first, routes A and B are classified according to their scheduled headways. As they are (on average) longer than 12 min, a punctuality analysis is run. Punctuality is measured by the percentage of punctual buses under the assumption of punctual arrivals ranging from between –60 s early and 180 s late. These percentages are linked to the related LoS derived from [53]. An ad hoc scale was arranged as follows: $LoS\ F$ means fewer than 50% of punctual arrivals and $LoS\ E$ is between 50 and 60%, and so on.

The outcomes of the punctuality analysis are shown in the control dashboard of Figures 6–8. As route A is very long, we reported only the portion that clearly includes the transfer stops, which are reported in bold. In each dashboard, the rows represent bus stops and the columns represent time periods. Each entry represents the LoS at that bus stop and at that time period.

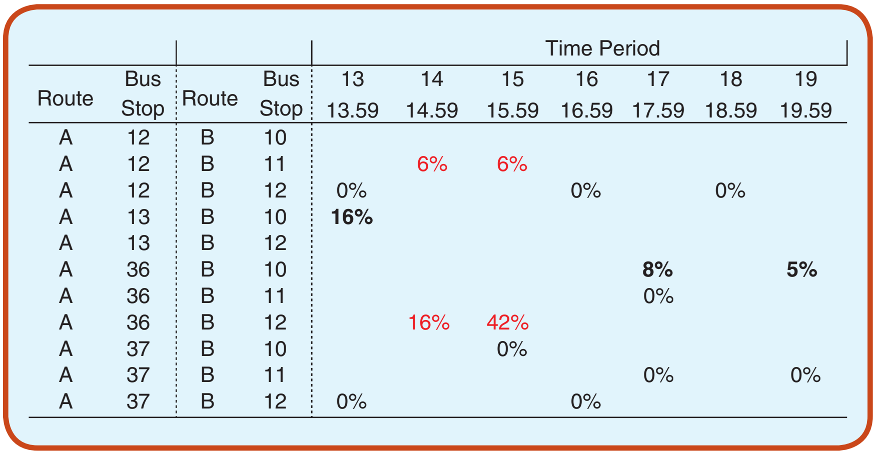
Figure 6 clearly shows that punctuality is not a problem for the northbound direction of route A at the bus stops and time periods of interest. Conversely, the southbound direction of route A (Figure 7) and the westbound direction of route B (Figure 8) show relevant punctuality problems (particularly from 15:00 to 19:59), which ostensibly affect the missed transfers.

As a result, a detailed analysis of unreliability sources was performed. As reported in part C) of the "Methodological Framework" section, this analysis included the investigation of sources at terminals, time spent at bus stops, and speed between bus stops. Moreover, the selection of the time period is a required step. Although the most critical time period was observed between 19:00 and 19:59, we focused on the interval between 13:00 and 13:59 because it presented critical punctuality problems affecting two unshared bus stops.

Because the terminal of route B is in the area of interest, the terminal analysis was performed for only route B and is reported in Table 2. It shows that D&SF were relevant at the departure terminal. Therefore, even if drivers had an adequate recovery time at the terminal, they failed to start the next run according to the scheduled headway. Only 1% of trips could not maintain the planned schedule due to the lack of available recovery time, and a mere 14% of the trips maintained the schedule as planned.

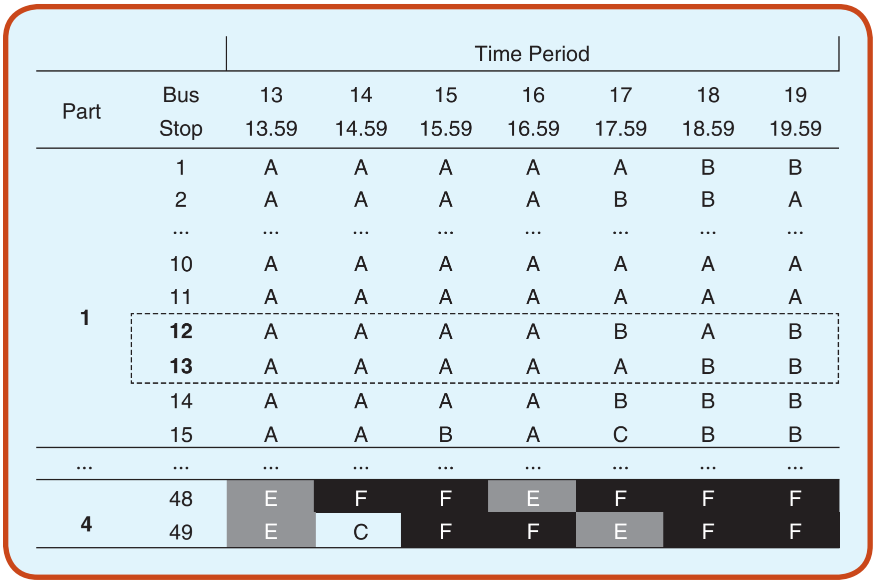
Table 1. A sensitivity analysis of time offset.

Time Offset (s)	Successful Transfers (#)	Scheduled Successful Rate (%)
<=60	221	36.8
60–120	296	49.3



				Time Period						
Route	Bus Stop	Route	Bus Stop	13 13.59	14 14.59	15 15.59	16 16.59	17 17.59	18 18.59	19 19.59
A	12	B	10							
A	12	B	11		6%	6%				
A	12	B	12	0%			0%		0%	
A	13	B	10	**16%**						
A	13	B	12							
A	36	B	10					**8%**		**5%**
A	36	B	11					0%		
A	36	B	12		16%	42%				
A	37	B	10			0%				
A	37	B	11					0%		0%
A	37	B	12	0%			0%			

FIG 5 The real success rates of routes A and B for the considered time periods.



		Time Period						
Part	Bus Stop	13 13.59	14 14.59	15 15.59	16 16.59	17 17.59	18 18.59	19 19.59
1	1	A	A	A	A	A	B	B
	2	A	A	A	A	B	B	A
	...	...	...	...	...	...	...	...
	10	A	A	A	A	A	A	A
	11	A	A	A	A	A	A	A
	12	A	A	A	A	B	A	B
	13	A	A	A	A	A	B	B
	14	A	A	A	A	B	B	B
	15	A	A	B	A	C	B	B
...	...	...	...	...	...	...	...	...
4	48	E	F	F	E	F	F	F
	49	E	C	F	F	E	F	F

FIG 6 The control dashboard on LoS punctuality at all bus stops and time periods for route A—northbound direction.

At the arrival terminal, approximately 97% of problem sources depended on ISD. Therefore, one may expect that the relationship between D&SF at the departure terminal and ISD at the arrival terminal could depend on the absence of available recovery time at the arrival terminal. This could be corrected by drivers through a larger-than-scheduled speed. In the following en-route analysis, we will seek a confirmation of this expectation.

The en-route analysis is reported in Figures 9 and 10 for the considered time period. Because the bus operator does not include the time spent at stops in its schedule (it is considered at terminals only), in this experimentation, the en-route analysis makes use of a derived scheduled of the time spent. It is computed by multiplying the average number of passengers (data gathered from manual surveys) at each bus stop by the average boarding time for passengers, which is supposed to be 2 s/pass. The boarding time for each passenger depends on the ticketing systems in use. As CTM uses an onboard proof-of-payment ticketing system [69] based on magnetic and contactless tickets, this value can be considered suitable. These values are not too dissimilar from those gathered in experimental studies [70], [71].

The computation of the averages of the real speed might be affected by exceptional values. This problem is addressed by removing the extreme values using bus-operator-dependent thresholds. Moreover, the speed analysis is performed in the case of a congestion speed of 10 km/h [72] to detect the uncontrollable external factors (UEF). Furthermore, a real speed ranging between 0.9 and 1.1 times the scheduled speed is set according to bus operator guidelines to detect ISD or D&SF, respectively.

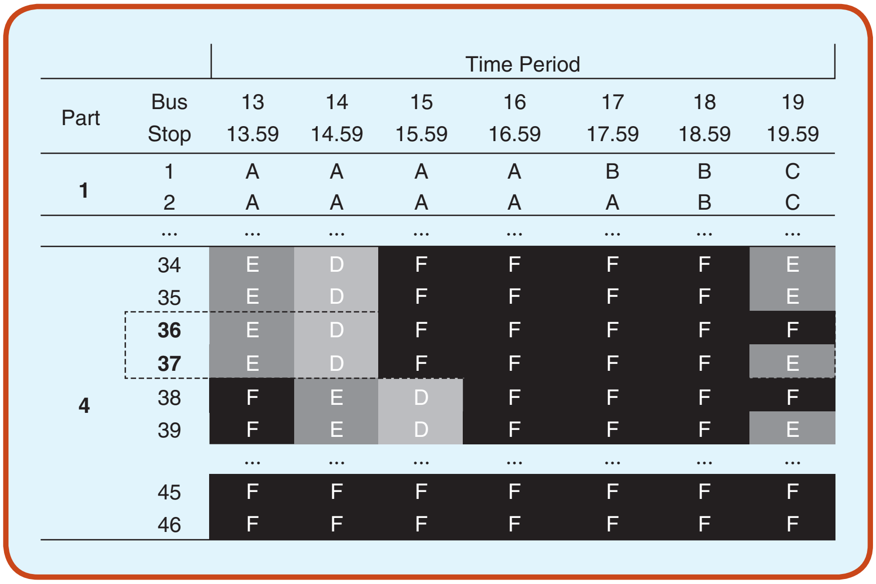
In Figures 9 and 10, two different dashboards are presented as well as are the percentage of the occurrence of unreliability sources with different colors and letters. For instance, the best situations are denoted as OK. Conversely, the worst conditions are marked differently. For the sake of space, Figures 9 and 10 report only the route's parts involved in transfers. More precisely,

- the top dashboard shows the analysis of the downstreaming sources and the time spent. The "E-E" notation represents the case in which a run ends early at the previous and at the current bus stop, "L-L" indicates the opposite case, and "Other" represents a mixed case. The L-UPV and U-UPV notations represent the cases in which the passenger volume is lower or higher than the expected one. The time spent is employed to understand whether or not problems at stops depend on the UPV. The transfer bus stops are represented in bold.

- the down dashboard shows the speed analysis used to detect the UEF, ISD, and D&SF along the route. The transfer bus stops are represented by a black circle.

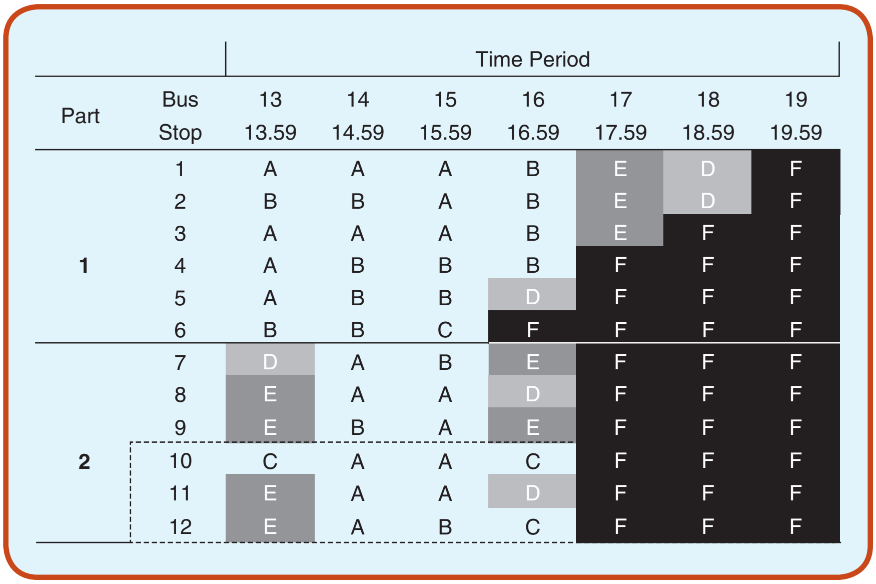
Interestingly, these dashboards point out that different sources may be relevant. The focus of the following analysis will be on the routes showing the most relevant punctuality problems and the bus stops involved in transfers. Therefore, we will neglect the northbound direction of route A.

Figure 9 shows the results of different problem sources along the southbound direction of route A. The downstreaming source analysis revealed that buses did not run as planned because the service was "OK" for fewer than 40% of cases. Moreover, the time-spent analysis confirms this negative trend because the quota of UPV was roughly 1.5-times larger than that of "OK." In addition, the bus stops affected by transfers had evident problems of ISD (100 and approximately 80% at bus stops 36 and 37, respectively) and were located in the last part of the route (i.e., part 4), where buses worsen their reliability from the beginning. In addition, the speed analysis shows that in part 1, the highest relative source was D&SF. Thus, even if the buses ran alongside a with-flow bus lane in part 1, they maintained larger-than-expected speeds. However, this "too-sporty" driving style may depend on the difficulty to guarantee the tight schedules at the end of the route, as ISD is recorded.



Part	Bus Stop	Time Period						
		13 13.59	14 14.59	15 15.59	16 16.59	17 17.59	18 18.59	19 19.59
1	1	A	A	A	A	B	B	C
	2	A	A	A	A	A	B	C
	...	...	...	...	...	...	...	...
4	34	E	D	F	F	F	F	E
	35	E	D	F	F	F	F	E
	36	E	D	F	F	F	F	F
	37	E	D	F	F	F	F	E
	38	F	E	D	F	F	F	F
	39	F	E	D	F	F	F	E
		...	...	...	...	...	...	...
	45	F	F	F	F	F	F	F
	46	F	F	F	F	F	F	F

FIG 7 The control dashboard on LoS punctuality at all bus stops and time periods for route A—southbound direction.



Part	Bus Stop	Time Period						
		13 13.59	14 14.59	15 15.59	16 16.59	17 17.59	18 18.59	19 19.59
1	1	A	A	A	B	E	D	F
	2	B	B	A	B	E	D	F
	3	A	A	A	B	E	F	F
	4	A	B	B	B	F	F	F
	5	A	B	B	D	F	F	F
	6	B	B	C	F	F	F	F
2	7	D	A	B	E	F	F	F
	8	E	A	A	D	F	F	F
	9	E	B	A	E	F	F	F
	10	C	A	A	C	F	F	F
	11	E	A	A	D	F	F	F
	12	E	A	B	C	F	F	F

FIG 8 The control dashboard on LoS punctuality at all bus stops and time periods for route B—westbound direction.

Table 2. A terminal analysis at the 13:00–13:59 time period for route B.

Terminals	D&SF (%)	ISD (%)	OK (%)
Departure	85	1	14
Arrival	3	97	0

Figure 10 displays the results of different problem sources along the westbound direction of route B. The downstreaming source analysis shows that buses usually ran according to the schedule. However, this favorable situation tended to decrease along the route, even if lower-than-expected passenger volumes may have increased the speed because buses did not dwell at each stop. Conversely, the speed analysis shows that reliability worsened along the route; indeed, ISD and UEF became relevant and may have affected transfers. These results are also confirmed by the characteristics

Time Period [13:00–13:59]		Downstreaming Analysis				Time-Spent Analysis		
Part	Bus Stop	E-E	L-L	Other	OK	L-UPV	U-UPV	OK
1	1 2	0%	7%	7%	86%	56%	7%	37%
…	…	…	…	…	…	…	…	…
4	34	30%	25%	5%	40%	62%	5%	33%
	35	33%	23%	2%	42%	65%	9%	26%
	36	**25%**	**31%**	**5%**	**39%**	**45%**	**12%**	**43%**
	37	**25%**	**31%**	**2%**	**42%**	**47%**	**10%**	**43%**
	38	20%	32%	14%	34%	49%	12%	39%
	39	19%	37%	10%	34%	61%	5%	34%
	…	…	…	…	…	…	…	…
	45	21%	5%	74%	0%	51%	14%	35%
	46	74%	2%	21%	3%	60%	10%	30%

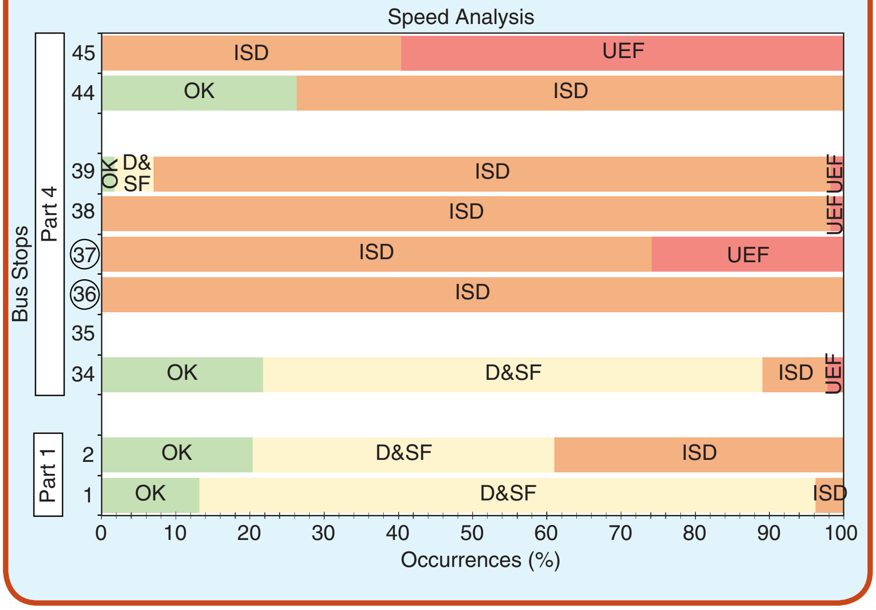


FIG 9 The control dashboards on the analysis of unreliability sources along the route from 13:00 to 13:59 route A—southbound direction. E-E: early-early; L-L: late-late.

of the route since part 2 presented mixed-traffic conditions. Moreover, as expected, the occurrence D&SF at the departure terminal could be explained by the information on missing recovery times at the arrival terminal. In summary, a too-tight schedule may generate these results and limit the success of scheduled transfers.

Finally, all of these results show that different strategies need to be investigated in different time periods and, possibly, within each time period. The drivers of route B often experienced low recovery times at the arrival terminal (see Table 2), thus it is recommended to revise the scheduled recovery time. Furthermore, it is strongly recommended to completely revise the schedule of route B as tight schedules are provided even if

L-UPV has high values along the route.

Conversely, to correct the unreliability along the southbound direction of route A, a different distribution of travel times is suggested due to the inversion of unreliability sources. The pursued decrease in speed in part 1 must be compensated by the increase of speed in part 4, where L-UPV and U-UPV have high values. They could be reduced by adjusting schedules. Therefore, these results show that in both routes, there should be a revision of the service design to improve the percentage of *RST*s.

Conclusion and Research Perspectives

Transfers can increase the flexibility of bus transit systems and, when they are not well planned and/or performed, there is a decrease in reliability due to the increase in transfer time for passengers. Much research has been done on the planning of synchronized transfers in timetable scheduling at the tactical level. Further research has investigated the deployment of real-time tactics to regulate the movement of vehicles and maintain the transfer synchronization at the operational level. Conversely, no attention has been devoted to check whether transfers are well planned and/or performed according to archived AVL data at the monitoring phase. Although AVL data provide many more details than do human-collected ones, they also give rise to additional challenges, such as measuring the effectiveness of transfers and detecting possible unreliability sources of missed transfers.

This article proposed the first offline framework for the analysis of transfers along routes, which can

- capture the transfers between pairs of origin routes (for alighting passengers) and destination routes (for boarding passengers) at shared (without walking time) and unshared (with admissible walking time) bus stops by processing AVL data
- focus on the transfer for any given pair of routes to point out bus stops and time periods in which scheduled and real transfers are not met

- measure the causes of unreliability of real transfers and disclose the related sources to alert who/which is responsible for the transfer unreliability.

The new framework can be applied to any standard AVL system and results in significant time and energy savings in the investigation of large data sets. User-friendly control dashboards show clear and synthetic outcomes from the analysis of transfer unreliability. The framework was widely tested in an experimentation using roughly 145,000 AVL real archived data records to show where transfer problems occur.

As the tested AVL technology records time-at-location data at each bus stop, it successfully handles the cases of buses that could be assigned to close bus stops (e.g., a generic bus may stop at one and skip another as it is within walking distance or it slows down there and boarding does not happen). In this case, the framework matches each bus stop to the other ones within walking distance and computes the rate of success of scheduled and real transfers.

Additional developments can be introduced. First, the proposed framework may be integrated with APC and automatic fare-collection systems for the accurate analysis of passenger data without any assumption on the time spent. Moreover, this integration would also be useful to select routes according to transfer volumes. Second, the sources of unreliability could also be identified using statistical methods such as principal component analysis and will be investigated in future works. Third, it would be interesting to investigate the efficiency of the computation for the framework in the case of more data and routes. Fourth, it would be of interest to integrate this framework into a web platform for an online setting to support PTCs' experts in evaluating the transfer's reliability. Indeed, they can be assisted in the planning stage because they are in the position to analyze sources and possibly select strategies that improve the reliability of transfers. For instance, one can revise timetables by using optimization approaches that maximize the number of simultaneous bus arrivals at transfer points. Finally, this research contributes to the monitoring of transfer reliability to provide a tool for service replanning. Were data from the tracking of passengers available, they could also be adopted for prediction of transfers by real-time messages to commuters to make the right transfer choice. These research topics have great relevance for future smart cities.

Time Period [13:00–13:59]		Downstreaming Analysis				Time Spent Analysis		
Part	Bus Stop	E-E	L-L	Other	OK	L-UPV	U-UPV	OK
1	1							
	2	1%	7%	8%	84%	85%	9%	6%
	3	0%	10%	13%	77%	79%	0%	21%
	4	0%	21%	10%	69%	100%	0%	0%
	5	0%	31%	14%	55%	85%	1%	14%
	6	0%	45%	17%	38%	62%	6%	32%
2	7	0%	40%	23%	37%	82%	1%	17%
	8	0%	45%	3%	52%	71%	1%	28%
	9	0%	44%	3%	53%	97%	0%	3%
	10	**0%**	**39%**	**8%**	**53%**	**6%**	**40%**	**54%**
	11	**0%**	**54%**	**7%**	**39%**	**14%**	**24%**	**62%**
	12	**0%**	**56%**	**6%**	**38%**	**0%**	**97%**	**3%**

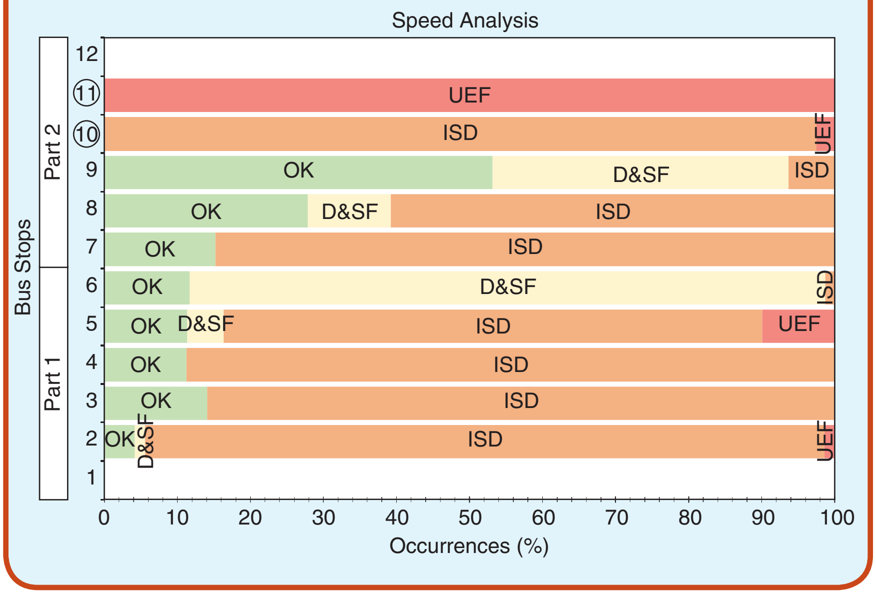


FIG 10 The control dashboards on the analysis of unreliability sources along the route from 13:00 to 13:59 route A—westbound direction.

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