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Transfer's monitoring in bus transit services by Automatic Vehicle Location data

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Abstract

Since transfers increase the connectivity of routes, they improve the characteristics of transit networks. Designing and managing transfers are well-investigated issues arising at the tactical and operational level. Conversely, the monitoring phase was rarely faced to verify the consistency between well planned and/or delivered transfers. In this paper, we tailor an innovative methodology for measuring the rate of transfers between two routes by using archived Automatic Vehicle Location (AVL) data. This measurement is performed spatially, at shared and unshared (but reasonably quite close) bus stops, and temporally at each time period. The results are represented by easy-to-read control dashboards. This methodology is tested by about 240,000 AVL real records provided by the local bus operator of Cagliari (Italy) and provides valuable insights into the characterization of transfers.

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Keywords: Big Data; Transfer diagnosis; Automatic Vehicle Location Data

1. Introduction

In public transport systems, transfers arise when no direct route links the origin and the destination, and/or several transport modes (*e.g.,* tram, bus) must be used in a trip. Hence, if passengers need to shift among routes, planning well connected and synchronized transfers is a key factor to decrease their inconvenience in this stage. Furthermore, since transfers increase the connectivity of routes owing to the flexibility of paths, they may support the improvement of transit networks. However, according to Ceder et al. (2001), Eranki (2004) and Barabino et al. (in press), transfers involve several inconveniences for passengers such as: (a) the need to walk to a 'close' bus stop; (b) the need to board a new vehicle; (c) the negative perception of the additional waiting time; (d) the possible additional delay during the trip. Therefore, the possible elimination of these inconveniences results in the challenging problems of designing,

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managing, and monitoring well-connected routes and schedules, to guarantee the maximum connectivity and the minimum transfer time (i.e., walking and/or waiting) for passengers.

Transfers in public transport are not a new topic for the scientific community. Much research has been done to design (at the tactical level) and manage (at the operational level) transfers. On the one hand, the research faced the challenge to design synchronised transfers. This research largely focused on (i) analytical modelling and (ii) mathematical programming methods. Analytical modelling showed elegant relationships between several transit system parameters and the demand for transit, operating costs, etc. However, these models are presented for idealized public transport (e.g., Sivakumaran et al., 2012; Kim and Schonfeld, 2014). Mathematical programming methods minimise the total passenger transfer times due to waiting (e.g., Wong et al., 2008; Shafahi and Khani, 2010) or maximize the number of synchronizations at shared stops from given dispatching headways (e.g., Ceder et al., 2001; Ibarra-Rojas and Rios-Solis, 2012) to determine the departure times of the daily trips. Other studies expanded the synchronization problem (e.g., Wang et al., 2017; Gkiotsalitis at al., 2020). Owing to their computational intractability, heuristics were proposed for these models. On the other hand, since the abundance of automatic vehicle location (AVL) has enabled tracking vehicles, other research investigated real-time tactics to control the motion of vehicles to keep the planned (synchronized) timetable (e.g., Dessouky et al., 2003; Hadas and Ceder, 2010). Conversely, only Hadas (2015) and Barabino et al. (in press) provided specific methodologies to verify if transfers are planned and/or performed effectively according to AVL data.

This paper contributes to the research on monitoring by the application of a portion of the methodology by Barabino et al. (in press) in a real case study. The methodology is organised in two steps and moves from archived AVL data. The first step pre-processes AVL raw data to return an adjusted data set without inconsistencies. The second step makes an evaluation of transfer's reliability to discover where (i.e., bus stops) and when (i.e., time period) planned and delivered transfers do not meet. This methodology integrates algorithms to addresses AVL data inconsistencies (e.g., Barabino et al., 2013a) and advances the research in Hadas (2015) by computing the successfulness of a real transfer against the scheduled one. Moreover, it manages the case of shared and unshared stops. In the first case, the routes in a transfer visit the same bus stop. The latter case occurs when two routes are not served be the same bus stops and are located within an acceptable walking distance. Unlike Barabino et al. (in press), this methodology was tailored to perform only a measurement of the transfers' rate of success. Moreover, it was applied to a real case with a skeleton and a feeder route, to investigate its viability when routes have very different frequencies. In this case study, the transfer synchronisation is relevant, especially when passengers need to shift from the skeleton to feeder route.

2. Methodology

In this section, the former methodology is synthetically presented to provide suitable AVL data and perform a measurement of transfer's reliability both in time and space. This methodology is organised in two steps: I) AVL data pre-processing and II) Transfer detection and evaluation. These stages are organized as shown in Fig. 1, which starts from the AVL data processing and finally reports the assessment of the transfer's reliability. The candidate, the scheduled and the real transfers are also indicated in Fig. 1.

Candidate transfers are all possible connections between two routes at shared and unshared bus stops and/or within a maximum time, which accounts for waiting time at shared bus stops and walking and waiting times at unshared bus stops. Scheduled transfers are all feasible transfers including 'simultaneous' arrivals detected in the original schedule. These 'simultaneous' arrivals may represent the arrival of two buses such that the time elapsed between consecutive arrivals is not larger than a tolerable waiting time (Eranki, 2004). Since our methodology embraces both shared and unshared bus stops, this definition is quite reasonable, because unshared transfers cannot be made without a maximum tolerable time. Real transfers represent the feasible 'simultaneous' transfer as detected in the service execution by using real AVL data. PTCs may select a target threshold (e.g., 80%) to evaluate the effectiveness of a scheduled transfer with respect to the candidate and a real transfer with respect to the scheduled one. Therefore, Fig. 1 shows that, if the target threshold is not meet, *ad hoc* analysis on routes may support the revision of the original schedule or the recognition of unreliability transfer's sources. Some indications on how to revise the schedules by time offsets are presented in this paper, whereas the methodology for the analysis of unreliability sources is reported in Barabino et al. (in press).

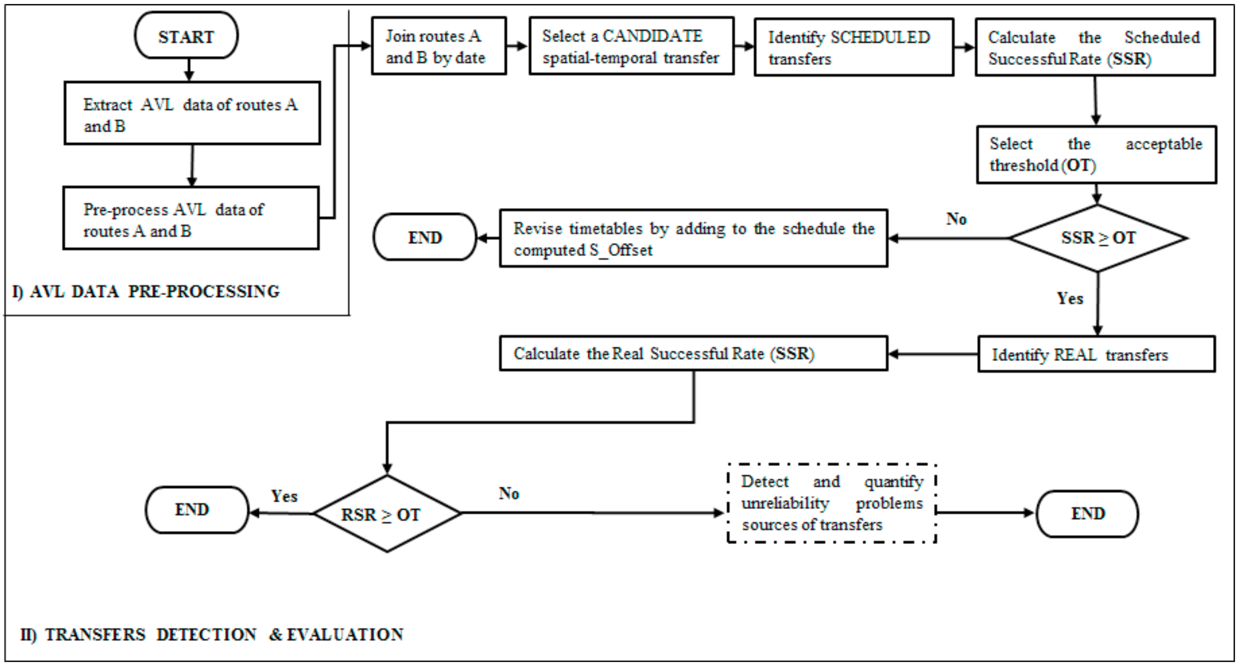

Fig. 1. The methodology for the measurement of transfers.

2.1. AVL data pre-processing

Consider two routes A and B sharing at least one bus stop (and their scheduled departure headways). For each route, select the archived AVL data from provided service database. The main attributes of AVL data in a typical architecture are date, vehicle-block (which is associated with the vehicle shift), route direction, trip number, bus stop code and order, actual and scheduled arrival times (or departure times). Finally, according to the specific AVL architecture, the time spent or the dwell time at each bus stop is retrieved. Next, the methodology performs proper AVL data handling on possible inconsistencies to account for Bus Overtaking (BO) and distinguish between missing data points (i.e., Technical Failures - TF or Incorrect Operation in Service - IOS). More precisely, no pass-up is supposed to occur and BO is faced as follows. First, actual arrival (or departure) times are chronologically ordered to consider the real bus arrivals at bus stop, since passengers neglect the right schedule of buses. Second, scheduled arrival (or departure) times are chronologically ordered to consider published schedules. Third, the former lists are joined. Missing data points are recognized by a monthly report of IOSs, which is merged with the original schedule and, next, with AVL data. In this methodology, any missing data is supposed to be a TF, unless it is a reported IOS. Therefore, two different ordered lists M_X^A and M_X^B of processed AVL data are returned for routes A and B, respectively. All details of AVL data pre-processing are reported in Barabino et al. (2013a), Barabino et al. (2015) and Barabino et al. (2017a).

2.2. Transfers Detection & Evaluation

<u>The identification of a candidate spatial-temporal transfer</u>

Let d be the date; I and J be the sets of all bus stops and H and K be the sets of runs for routes A and B, respectively; W be the set of candidate transfers, which are possible in terms of space and time; SAT^{A}_{ihd},(or SDT^{A}_{ihd}), RAT^{A}_{ihd} (or RDT^{A}_{ihd}), SAT^{B}_{jkd},(or SDT^{B}_{jkd}), RAT^{B}_{jkd} (or RDT^{B}_{jkd}) be the scheduled and the real arrival (or departure) times at bus stops $i \in I$ and $j \in J$ for routes A and B, on date d, respectively; $SDH^{At}_{i(h,h-1)}$ 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 and finally, $SDH^{B,t}_{j(k,k-1)}$ 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. In the analysis of

M_X^A and M_X^B, records from routes A and B are joined according to d. Next, a search of shared and unshared bus stops in the space and time domain is made and candidate transfers are searched as follows.

First, for each date d, each record in M_X^A is extracted and joined to each record in M_X^B. Next, a spatial circular boundary of radius δ, which reflects the maximum acceptable walking distance between two bus stops is created for each record in M_X^A. Clearly, if $\delta = 0$, bus stops are shared. Moreover, temporal boundaries of length $SDH^{At}_{i(h,h-1)}$ and $SDH^{B,t}_{j(k,k-1)}$ are created according to the maximum waiting (and walking) time to make a transfer from route A (or B) to route B (or A) for each time period.

Second, the geographical or Euclidean distance – depending on the coordinates in use – between bus stops $i \in I$ and $j \in J$ is computed and denoted by $dist_{ij}$ to point out the spatial length between two bus stops.

Third, the temporal length (denoted by $time_{ij}$ and $time_{ji}$) between bus stops $i \in I$ and $j \in J$ are computed as follows:

$$time_{ij} = (SDT^B_{jkd} - SAT^A_{ihd}) \qquad \forall\, i \in I;\ \forall j \in J \tag{1}$$

$$time_{ji} = (SDT^A_{ihd} - SAT^B_{jkd}) \qquad \forall\, i \in I;\ \forall j \in J \tag{2}$$

Eqns. (1) and (2) consider the time interval to make a (possible) bidirectional transfer from routes.

Fourth, for each pair of records in M_X^A and M_X^B, a candidate transfer is denoted by $w_{ij} \in W$ and identified as follows:

$$w_{ij} = \begin{cases} 1\ if \begin{cases} 0 \le dist_{ij} \le \delta & \forall\, i \in I;\ \forall j \in J \quad (3.1) \\ \text{and} \\ 0 \le time_{ij} \le SHD^{B,t}_{j(k,k-1)} & \forall\, i \in I;\ \forall j \in J \quad (3.2) \\ \text{and} \\ 0 \le time_{ji} \le SHD^{A,t}_{i(h,h-1)} & \forall\, i \in I;\ \forall j \in J \quad (3.3) \end{cases} \\ else\ 0 \end{cases} \tag{3}$$

Eqns. (3.2) and (3.3) highlight that a successful temporal transfer needs for a maximum of transfer time, which depends on the scheduled headways of the routes at hand, because passengers may spend this time to reach an unshared bus stop and have a short waiting time before boarding. Both eqns. (3.2) and (3.3) are mandatory to guarantee a transfer from both routes (*i.e.* bidirectional).

Fifth, the list of all the possible candidate transfers is reordered in terms of increasing date, bus stop number, $dist_{ij}$, $time_{ij}$ and $time_{ji}$. A new array PT is generated to save the list of potential transfers.

Sixth, the total number of all records (i.e, TT) in PT is computed as follows:

$$TT = \sum_{i\in I} \sum_{j\in J} w_{ij} \tag{4}$$

<u>Scheduled transfer identification and successful rate computation</u>

Let S be the set of scheduled transfers and v_p be the pedestrian speed. Once each candidate transfer $w_{ij} \in$ W is identified, the method identifies the scheduled transfer and determines its success rate. First, for each w_{ij} of PT, the walking time (between these bus stops) is computed as follows:

$$Walking\_time_{ij} = \frac{dist_{ij}}{v_p} \qquad \forall\, i \in I;\ \forall j \in J \tag{5}$$

If the bus stops are shared, eqn. (5) returns zero.

Second, the latest arrival and the earlier scheduled departure times of route A and B are denoted by S_A_{ij} and S_D_{ij} and computed as follows:

$$S\_A_{ij} = max\ (SAT^A_{ihd};\ SAT^B_{jkd}) \qquad \forall\, i \in I;\ \forall j \in J \tag{6}$$

$$S\_D_{ij} = min\ (SDT^A_{ihd};\ SDT^B_{jkd}) \qquad \forall\, i \in I;\ \forall j \in J \tag{7}$$

Eqns. (6) and (7) return data input for the calculation of the scheduled time offset that makes possible the transfer between routes A and B, respectively, and *vice versa*. For instance, if route A arrives and departures before the arrival of route B, passengers of route A can board on route B, but the converse does not hold. Hence, the scheduled time offset S_Offset_{ij} is computed as follows:

$$S\_Offset_{ij} = (S\_D_{ij} - S\_A_{ij}) \qquad \forall\, i \in I;\ \forall j \in J \tag{8}$$

Eqn. (8) shows that a positive S_Offset_{ij} enables passengers to make a transfer from route A to route B and *vice versa* (at least at shared bus stops). Conversely, a negative S_Offset_{ij} is the minimum time compensating for the missed transfer. This time should be added to the original schedule to enable the transfer.

Third, the scheduled transfer (ST_{ij}) is computed as follows:

$$ST_{ij} = \begin{cases} 1 \; if \; \begin{cases} Walk\ time_{ij} \leq S_{Offset_{ij}} \leq Max\left(SDH^{At}_{i(h,h-1)}; SDH^{Bt}_{i(k,k-1)}\right) \\ \forall\, i \in I;\ \forall j \in J;\ \forall\, h \in H;\ \forall k \in K \end{cases} \\ else\ 0 \end{cases} \quad (9)$$

Eqn. (9) helps identify if a candidate transfer between $i \in I$ and $j \in J$ is a successful scheduled transfer according to S_Offset_{ij}. The first part of eqn. (9) shows that S_Offset_{ij} must be larger or equal to $Walk\ time_{ij}$. This situation happens when bus stop $i \in I$ and bus stop $j \in J$ are quasi-shared because passengers must walk from the arrival bus stop towards the departure one. The last part of eqn. (9) sets a maximum of S_Offset_{ij} to make the transfer feasible within a time interval, which is set as the maximum between the time headways of routes A and B. The arrivals of vehicles are assumed not to exceed a tolerable transfer time reflecting the worst possible operating conditions (i.e., the service is irregular). This tolerable time includes walking and waiting in the case of unshared bus stops, or only waiting time in the case of shared bus stops. It is worth noting that Eqn. (9) reflects real situations. For example, in two unshared bus stops, passengers alighted from route A at bus stop $i \in I$ could cross the way to board the route B at bus stop $j \in J$ and *vice versa*. The inequality $S\_Offset_{ij} \geq Walk\ time_{ij}$ guarantees the passenger walk from bus stop $i \in I$ to bus stop $j \in J$ and *vice versa*. Moreover, if S_Offset_{ij} is lower than or equal to the maximum value among headways, passengers have a tolerable waiting time at bus stops $i \in I$ and $j \in J$. Note that the calibration of the maximum headways may also include the walking time to move from the alighting bus stop to the boarding one.

Fourth, the total number of scheduled successful transfers (*SST*) is computed as follows:

$$SST = \sum_{i \in I} \sum_{j \in J} ST_{ij} \quad (10)$$

Fifth, the rate of scheduled success transfers for each bus stop (shared and unshared) and time period *t* is computed as follows:

$$SSR^{t}_{ij} = 100 * \frac{SST}{TT} \qquad \forall\, i \in I;\ \forall j \in J \quad (11)$$

Finally, the last step shows where one must pay attention 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 reached, some actions need to correct transfer reliability. More precisely, this step works according to these rules:

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

Real transfer identification and successful rate computation

Once, $SSR^{t}_{ij} \geq$ OT, the method identifies the real transfer and, next, computes its success rate, as follows. Let *R* be the set of real transfers.

First, the latest arrival and the earlier real departure times of route A and B are denoted by R_A_{ij}, R_D_{ij}, and computed as follows:

$$R\_A_{ij} = max\ (RAT^{A}_{ihd}\,;\ RAT^{B}_{jkd}) \qquad \forall\, i \in I;\ \forall j \in J \quad (12)$$

$$R\_D_{ij} = min\ (RDT^{A}_{ihd}\,;\ RDT^{B}_{jkd}) \qquad \forall\, i \in I;\ \forall j \in J \quad (13)$$

Eqns. (12) and (13) return data input to the calculation of the real time offset that makes possible the transfer between route A and B, respectively, and vice versa. This real time offset is denoted by R_Offset_{ij} and is computed as follows:

$$R\_Offset_{ij} = (R\_D^{BA}_{ij} - R\_A^{BA}_{ij}) \qquad \forall\, i \in I;\ \forall j \in J \quad (14)$$

Second, the real transfer (RT_{ij}) is computed as follows:

$$RTij = \begin{cases} 1\ if\ \left(Walk\ time_{ij} \leq R\_Offset_{ij} \leq Max(RDH^{At}_{i(h,h-1)}; RDH^{Bt}_{i(h,h-1)})\right) \\ else\ 0 \end{cases} \quad (15)$$

Third, when each real transfer is marked as success or fail, the total number of real successful transfers (RST) is computed as follows:

$$RST = \sum_{i \in I} \sum_{j \in J} RT_{ij} \quad (16)$$

Fourth, the rate of a success of real transfers is computed for each bus stop and time period *t* as follows:

$$RSR^t_{ij} = 100 * \frac{RST}{SST} \quad \forall\, i\, \in I;\ \forall j\, \in J \tag{17}$$

Finally, the value of RSR^t_{ij} is compared to the OT to show if one must correct the unreliability of real transfers. This step works as follows: (i) if $RSR^t_{ij} \geq$ OT, the overall method ends, because the transfers are effectively planned and provided, thus no corrective action is required; (ii) if $RSR^t_{ij} <$ OT, the PTC is strongly advised to detect and quantifying unreliability problems sources of transfers to detect insights on why missed transfers occur.

3. Real-word experiment

This methodology has been experimented in the bus transport system in area of Cagliari, which is located on the island of Sardinia (Italy). The local operator is called CTM. It operates with 271 buses and trolleys and serves approximately 40.8 million trips a year. Moreover, buses and trolleys run over 12.4 million kilometres per year along 34 routes (CTM, 2020). CTM is interested in the improvement system reliability by the analysis of transfers at bus stops. For the sake of synthesis, the overall method is tested considering two routes: a skeleton and a feeder. These routes include both shared and unshared bus stops and have been chosen because of their characteristics. The skeleton route links the central area of the city with an external neighbourhood. It presents two directions that are denoted by A11 and R11. A11 moves along the northbound direction for about 8.7 km long with 30 bus stops. R11 moves along southbound direction for about 10.4 km with 38 bus stops. Its headway is 7 minutes (on average) from 7.00 to 20.59. This route is operated by low floor standard vehicles with a capacity of 105 passengers. The feeder route links a peripheral area of the main city with a residential neighbourhood. This route is denoted by A01 and moves along a clockwise path about 8.3 km long with 31 bus stops. Its headway is 27 minutes (on average) from 7.00 to 20.59. This route is operated by low floor middle vehicles having a capacity of 70 passengers. Route A11 shares the same bus stop with the clockwise direction of route A01. This bus stop is the 21 for route A11 and 25 for route A01. Route R11 shares the same bus stops with the clockwise of route A01. These bus stops are denoted by 19 and 20 for route R11, and 2 and 3 for route A01.

Since 2007, all buses have been equipped with a specific AVL architecture. It mainly records actual and scheduled arrival times at each stop and make daily available about 100,000 AVL data records on the whole network (Tilocca et al., 2017). In this experiment, AVL data were collected from 05.00 to 20.59, but only the period from 09.00 to 19.59 is investigated for the sake of ease. Moreover, data on 13.00 and 14.59 are not available because route A01 is not operated. The AVL data of these routes are collected in weekdays of March 2019. According to step I) of the method, BO is addressed by ordering data consistent with actual transit times. Temporal gaps due to TF were detected and processed while IOSs were neglected owing to the minor number. At the end of stage I), 238,005 AVL records were processed: 193,981 for routes A11 and R11, and 44,024 for route A01, respectively. Next, the methodology was implemented according to step II). For this experiment, δ was equal to 400 m (*e.g.*, Murray, 1998). Moreover, for each pair of $i\, \in I$ and $j\, \in J$, each candidate transfer w_{ij} was identified to check if it was successfully performed. Next, the total numbers of candidate transfers (*i.e.,* TT) was computed according to eqn. (4). A total of 1061 candidates were identified. Next, setting v_p = 4 km/h (*e.g.*, Fitzpatrick, 2006), the number of scheduled transfers was computed according to eqns. from (5) to (10). A total of 178 successful scheduled transfers is reported. Therefore, the rate of success is 16.8%, which is a low percentage. Next, the scheduled successful rate (*i.e.*, SSR^t_{ij}) is computed by eqn. (11), for each time period and pair of bus stops. This result is shown in Fig. 2 (a), where columns 1 and 3 represent the route of interest and columns 2 and 4 the bus stops for the transfer. Columns from 5 to 14 represent time periods. Each entry in columns represent the success rate of a transfer between route A11 and A01 and R11 and A01, respectively. The shared bus stops are edited in bold. Yet, all bus stops in Fig. 2 (a) are located within an acceptable walking distance. Fig. 2 (a) clearly point out that: (a) candidate transfers miss in several bus stops for each time period (the entries of these data are blank); (b) several candidate transfers are not realized. Only some transfers are successfully implemented and only on shared bus stops (*i.e.*, 21 and 25, 19 and 2, and 20 and 3) in few time periods (*i.e.* 09.00-09.59, 11.00-11.59, 16.00-16.59, 17.00-17.59 and 19.00-19.59). Moreover, Fig. 2 (a) confirms that PTCs aims to determine dispatching times of each route in isolation (*e.g.*, Gkiotsalitis et al., 2020), as the entries different from 0% are few. Hence, usually transfers do not look well planned. However, since high transfer times are not desirable, the PTCs may apply control strategies to increase the chance to finalise the transfers. Interestingly, if OT is equal to 80%, the relationship $SSR^t_{ij} <$ OT occurs in most of the cases. Therefore, the PTC is advised to adjust time offsets whenever the former inequality holds. In this experiment the total number of transfers needing revision equals 883 if the time offset is equal to 240 s. The PTC may synchronize about 53 % of transfers and this outcome could be particularly beneficial for unshared bus stops (Table 1). In the "lucky" cases of $SSR^{t}_{ij} \geq OT$, the identification of real transfers and the computation of the *RSR* is performed according to the step II) of the method. More precisely, only 24 successful real transfers are observed according to equations from (12) to (16). Therefore, the *RSR* is 13.5%, which is a low percentage as well. Next, the specific real successful transfer rate (*i.e.*, RSR_{ij}) is computed for each time period and pair of bus stops by eqn. (17). The outcomes are reported in the control dashboard of Fig. 2 (b). It shows that most scheduled transfers are not realized. Only a small percentage of transfers is implemented. Remarkably, the largest values of RSR_{ij} are obtained between the shared bus stops 19 and 20 of route R11 and 2 and 3 of route A01. Since in some bus stops $RSR_{ij} > 0$, $RSR_{ij} < OT$, a diagnosis of unreliability sources of missed transfers is of interest. This diagnosis goes beyond the objective of this paper. It is showed in Barabino et al. (in press), where further algorithms were integrated into the methodology (i.e., Barabino et al., 2017b; Barabino et al., 2017c; Mozzoni et al., 2017 and Barabino and Di Francesco, 2021).

Route	Bus Stop	Route	Bus Stop	09:00 09:59	10:00 10:59	11:00 11:59	12:00 12:59	15:00 15:59	16:00 16:59	17:00 17:59	18:00 18:59	19:00 19:59
A11	18	A01	29	0%								
A11	18	A01	3					0%				
A11	18	A01	5	0%	0%							
A11	19	A01	2						0%	0%	0%	
A11	19	A01	23							0%		
A11	19	A01	29								0%	
A11	19	A01	3			0%						0%
A11	19	A01	30									
A11	19	A01	31		0%		0%					0%
A11	20	A01	23				0%				0%	
A11	20	A01	24						0%			
A11	20	A01	25								0%	
A11	20	A01	29					0%				
A11	20	A01	30							0%		
A11	21	A01	24							0%	0%	
A11	**21**	**A01**	**25**									**100%**
A11	21	A01	31									
R11	17	A01	23			0%	0%					
R11	17	A01	24	0%					0%		0%	
R11	17	A01	25					0%				0%
R11	18	A01	25					0%				
R11	18	A01	29			0%						
R11	**19**	**A01**	**2**	**100%**		**100%**			**100%**	**100%**		
R11	19	A01	29								0%	
R11	19	A01	3	0%		0%						
R11	19	A01	30									
R11	19	A01	31	0%	0%			0%				
R11	**20**	**A01**	**3**	**100%**		**100%**			**100%**			
R11	21	A01	3									
R11	21	A01	6			0%						0%

Route	Bus Stop	Route	Bus Stop	09:00 09:59	10:00 10:59	11:00 11:59	12:00 12:59	15:00 15:59	16:00 16:59	17:00 17:59	18:00 18:59	19:00 19:59
A11	18	A01	3					0%				
A11	18	A01	5	0%	0%							
A11	18	A01	29	0%								
A11	19	A01	2						0%	0%	0%	
A11	19	A01	3			0%						0%
A11	19	A01	23							0%		
A11	19	A01	29								0%	
A11	19	A01	30									
A11	19	A01	31		0%		0%					0%
A11	20	A01	23				0%				0%	
A11	20	A01	24						0%			
A11	20	A01	25								0%	
A11	20	A01	29					0%				
A11	20	A01	30							0%		
A11	21	A01	24							0%	0%	
A11	**21**	**A01**	**25**									0%
A11	21	A01	31									
R11	17	A01	23			0%	0%					
R11	17	A01	24	0%					0%		0%	
R11	17	A01	25					0%				0%
R11	18	A01	25					0%				
R11	18	A01	29			0%						
R11	**19**	**A01**	**2**	**14%**		**13%**			**11%**	**17%**		
R11	19	A01	3	0%		0%						
R11	19	A01	29								0%	
R11	19	A01	30									
R11	19	A01	31	0%	0%			0%				
R11	**20**	**A01**	**3**	**7%**					**5%**			
R11	21	A01	6			0%						0%
R11	21	A01	3									

Fig. 2. (a) Scheduled success rates of routes A11, R11 and A01 for the considered time periods; (b) Real Success Rates of routes A11, R11 and A01 for the considered time periods.

Table 1: Sensitivity analysis of time offset.

Time offset [s]	Successful transfers [#]	Scheduled successful rate [%]
<= 60	110	12.5%
60-120	129	14.6%
12-180	420	47.6%
180 - 240	463	52.5%

4. Conclusions

Transfers increase the flexibility of the transit networks, but missed transfers decrease the reliability of transport networks because passengers need to wait for another run. Past research investigated the planning of synchronised transfers as an element of the timetable scheduling at the tactical level. Moreover, owing to Automatic Vehicle Location (AVL), other research has focused on the implementation of real-time tactics to control the motion of vehicles to maintain the transfer synchronisation at the operational level. Contrariwise, few attentions have been dedicated to check *a posteriori* if transfers are well designed and/or delivered using archived AVL data during the monitoring phase. This phase is key for the efficient operational planning of spatial and temporal well-connected routes.

This paper contributes to the research in this field, because it runs an innovative methodology for measuring the rate of transfers along skeleton and feeder routes to: (i) account for the topological properties of bus networks, such as shared and unshared (but reasonably quite close) bus stops; (ii) handle AVL data to draw attention to bus stops and time periods where designed and delivered transfers are not encountered. This methodology demonstrates the usefulness of an accurate AVL system and leads to significant time savings when huge amount of data needs to be investigated. Clear and synthetic outcomes on transfer measures were shown by intelligible control dashboards. The methodology has been largely experimented by about 240,000 real archived AVL data records, to show where and when transfers problems occur. This research may be of interest for transit industry practitioners to improve the service quality on routes for benchmarking and/or certification purposes consistent with norms (*e.g.*, EN 13816, 2002).

Nevertheless, further developments are listed. First, possible sources of unreliability owing to missed transfers may be investigated in these routes. Hence, practitioners can be assisted in the planning stage because they can select preventive strategies to improve the transfers reliability. Second, a challenging research is the real-time prediction of exact location of timed transfers, which may be notified to each passenger by mobile apps. Finally, the integration of this framework in a wider service quality managerial tool will be investigated (Barabino et al., 2013b; Barabino, 2018). These research topics may greatly influence future Smart Cities.

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