SERVICE RELIABILITY IN A NETWORK CONTEXT: IMPACTS OF SYNCHRONIZING SCHEDULES IN LONG HEADWAY SERVICES

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ABSTRACT

This paper presents research on synchronization of transfers and its impact on service reliability from a passenger perspective. Passenger reliability is analyzed for the case of a multi-operator transfer node. A method is developed to calculate the passenger centered reliability indicators: additional travel time and reliability buffer time, using scheduled and actual vehicle arrival and departure times as an input. Five major factors are identified as affecting reliability at a particular transfer: scheduled transfer time, distributions of actual arrivals of the first and second line, headways, transfer walking time, and transfer demand. It is demonstrated in a real network case that changing a specific transfer has effects on other transfers from the transfer point. This method can be applied in a cost benefit analysis to identify the benefits and costs of reliability for different groups of passengers, thereby supporting proper decision making.

1. INTRODUCTION

Service reliability in transit operations is gaining increasing attention from transit operators and researchers. Passengers benefit from increased reliability in the form of decreased and more predictable travel times, while operators can benefit from lower costs and potential for increased ridership (*1*) .

In addition to operational level, reliability improvements can come from the strategic (network design) and tactical (schedule design) levels (*2*,*3*). Both (*2*) and (*3*) were done for a single transit line, without considering network effects and transferring passengers. A next step is to extend this work to include transferring passengers in the calculation framework, and to study the effect of transfer synchronization on reliability. In the Netherlands 28% of national rail passengers continue their journey by some other form of public transportation (*4*).

Much work has been done regarding the synchronization of transfers and the effect on travel time (*5*,*6*,*7*,*8*). In these works, reliability is implicitly considered, as the total average travel time does depend on the reliability of the service. These works also generally consider one isolated transfer in one direction, which ignores the fact that shifting the schedule for one transfer will have an impact on the scheduled transfer time and reliability for several related transfers.

This paper presents an extension of the Van Oort (*1*) calculations to include a transfer and analyzes the major variables that affect reliability at a transfer. This new method is then used to determine the effects of scheduled transfer time on reliability for the case of a multi-level transfer point between an urban and a regional system. This paper presents the case of equal long headways on all services. For details of the method for other headway combinations see (*9*).

The paper is presented as follows. Section 2 provides background on service reliability in transit operations. Section 3 introduces the nuances of a transfer point as they relate to reliability, which leads to the calculations of the passenger related reliability indicators additional travel time (ATT) and reliability buffer time (RBT). Section 4 shows the effect on reliability for varying scheduled transfer times in a hypothetical network and Section 5 shows a real data example.

2. SERVICE RELIABILITY

Reliability has been demonstrated to be important to the traveler. Arriving when planned is among the most important attributes of a transit service (*10*), additional waiting and in-vehicle time have a higher disutility than expected waiting and in-vehicle time (*11*), and reliability is a factor in both route choice (*12*,*13*,*14*) and mode choice (*12*,*14*).

Service reliability from a passenger's perspective is based on the passengers' actual travel times. A route with consistent travel times, as compared to the schedule, would be considered as reliable, while a route with a greater variation among travel times would be considered as less reliable, because there is a greater chance that the passenger will arrive outside of their preferred time range.

Reliability can be measured by two characteristics of the distribution of actual travel times (Figure 1). First is additional travel time, calculated as the difference between the average actual travel time and the scheduled travel time (*15*). In most cases, as shown in the graph, the actual travel time will be greater than the scheduled travel time, which represents the travel time in the case of perfect operations. Second, the width of this distribution gives an indication of the variation among travel times. One way to measure this is reliability buffer time, calculated as the difference between the 95th and 50th percentile of the travel time distribution (*16*). The 95th percentile of travel time is used as an idea of how much time a passenger would need to budget to make a trip if they would like to arrive on time 19 out of 20 times, thought to be an acceptable on-time rate for commuters.

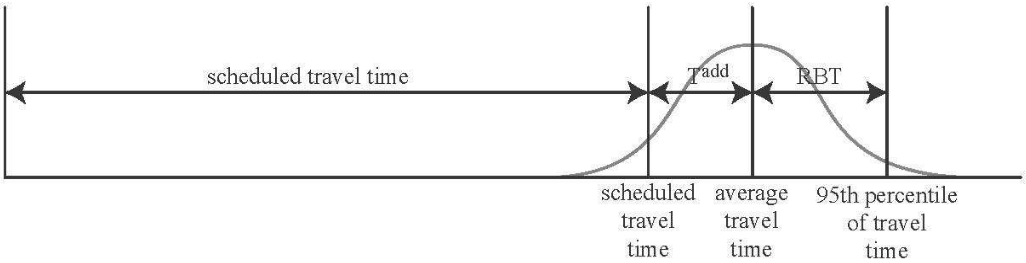

FIGURE 1 Passenger reliability indicators: additional travel time (T^{add}) and reliability buffer time (RBT).

Van Oort (*1*) shows that passenger related reliability can be explained as the relation between vehicle operations and passenger behavior. In Van Oort et al. (*2,17*), additional travel time is a function of additional waiting time and additional in-vehicle time. In this paper, additional transfer time is added in order to describe the reliability for transferring passengers.

3. RELIABILITY FOR TRANSFERRING PASSENGERS

This section explains the calculation methods for reliability of transferring passengers, which should be used in conjunction with Van Oort's (*1*) calculations for direct passengers. Then the important variables leading to travel time variation for transferring passengers are identified and discussed.

A passenger's journey through a transfer point can have a significant variation, and thus impact on reliability, due to the possibility that one or both vehicles can be missed (*8*). It is known that passengers prefer a transfer scenario that has a lower variability of out-of-vehicle time (*18*).

3.1 Calculation of reliability for transferring passengers

A scheduled transfer consists of the arrival of one vehicle, a walking time to the next vehicle, and a scheduled buffer time, often added in case of the late arrival of the first vehicle. Here, the scheduled transfer time will be referred to as the time between the scheduled arrival of the first vehicle and the scheduled departure of the second vehicle. All of these elements can be represented as distributions (Figure 2).

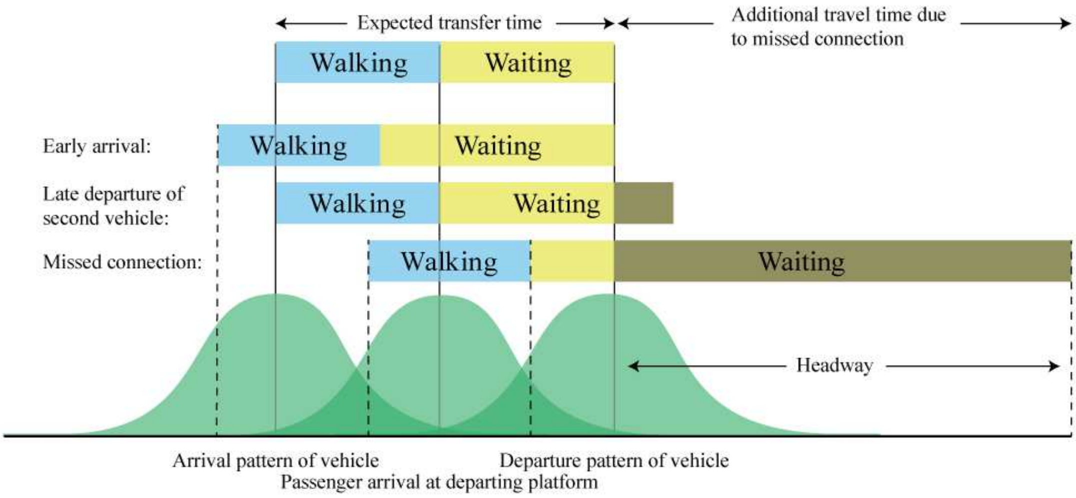

FIGURE 2 Stochastic distributions involved in a transfer.

In the case of long headways (longer than 12 minutes), passengers arrive at the initial stop according to a distribution around the scheduled departure time (*1*,*19*,*20*). These passengers can either make their planned vehicle, or miss it and wait for the next one. In case of short headway service passengers tend to arrive at random. See (*3*) for calculation methods in that scenario.

In (*17*), the passenger arrival pattern is simplified to assume that all passengers arrive at a certain time τ^{early} before the scheduled departure. It is assumed that passengers do not experience additional travel time if the vehicle departs within the time frame between τ^{early} and τ^{late}. This represents the accepted departure interval of the vehicle, according to the passengers. A vehicle that departs before τ^{early} causes all passengers to miss the vehicle and an additional travel time equal to the wait for the next vehicle. A vehicle that departs after τ^{late} causes all passengers to have an additional travel time equal to the difference between the actual and scheduled departure times.

Figure 2 shows that the variation in travel times of waiting time and in-vehicle time over the first leg does not affect the arrival time at the destination stop, provided the connection is not missed. A positive additional in-vehicle time, leads to an equally less amount of transfer time, while a negative additional in-vehicle time leads to an equally more amount of transfer time. To reduce complexity we neglect the impact on passenger experience due to other weights of travel time elements (*21*).

There are two ways that the individual components of a transfer can have an effect on the final travel time variation. Additional transfer time, due to a late departure of the connecting vehicle, leads directly to additional travel time. A missed connection means that the passenger has to wait for the next vehicle, leading to an increase in transfer time, and increase in travel time.

For transferring passengers, the final travel time distribution is a function of whether or not the connection is made or missed, the delay of the departure of the connecting vehicle and the additional in-vehicle travel time of the second leg of the trip.

The above sections show that calculating the additional travel time for transferring passengers, for long headways, depends on whether or not they make their initial vehicle, in combination with their transfer. This leads to four groups of passengers. Passengers that “Make” both their initial vehicle and their connection, those that “Make” their initial vehicle and “Miss” their transfer, passengers that “Miss” their initial vehicle and “Make” their intended transfer and passengers that “Miss” their initial vehicle and then “Miss” their transfer. This is illustrated in Figure 3.

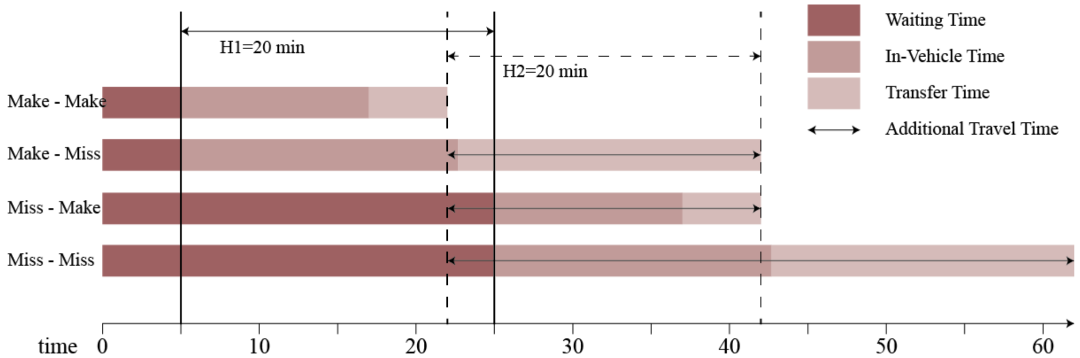

FIGURE 3 Pictorial representation of travel time needed before boarding the second vehicle for the four categories of transfer passengers.

The calculations use the following input data, which can be gathered by transit operators using Automatic Vehicle Location systems. In this case, consider a transfer from line *l* to line *m*.

$A^{sched}_{l,i,j}$ = Scheduled arrival time of vehicle *i* at stop *j* on line *l*.

$A^{act}_{l,i,j}$ = Actual arrival time of vehicle *i* at stop *j* on line *l*.

$N^{trans}_{l-m,i,j}$ = Number of passengers transferring from line *l* to line *m* in vehicle *i* at stop *j*.

$D^{sched}_{m,i,j}$ = Scheduled departure time of vehicle *i* at stop *j* on line *m*.

$D^{act}_{m,i,j}$ = Actual departure time of vehicle *i* at stop *j* on line *m*.

The calculation for additional waiting time in the case of long headways for non-transferring passengers, is shown in Equation 1 (*16*). The same divisions can be used to divide transferring passengers into "Make" and "Miss" groups for their initial vehicle.

$$T_1(l,i,j)^{\uparrow}(add,waiting) = \{\blacksquare(D_1(l,i+1,j)^{\uparrow}act - D_1(l,i,j)^{\uparrow}sched\&if\&D_1(l,i,j)^{\uparrow}act \leq \tag{1}$$

Then, the number of passengers that "Make" and "Miss" the connection is defined by Equation 2 and Equation 3.

$$P_{l-m,i,j}^{make} = N_{l-m,i,j}^{trans} \times P\left(t_{l-m,i,j}^{platform} \leq D_{m,i,j}^{act}\right) = \int_{-\infty}^{D_{m,i,j}^{act}} F(x)dx \tag{2}$$

$$P_{l-m,i,j}^{miss} = N_{l-m,i,j}^{trans} - P_{l-m,i,j}^{make} \tag{3}$$

where:

$$t_{l-m,i,j}^{platform} = A_{l,i,j}^{act} + t_{l-m}^{walk} \tag{4}$$

and:

t_{l-m}^{walk}	=	Walking time from the arrival platform on line *l* to the departure platform on line *m*.
$t_{l-m,i,j}^{platform}$	=	Arrival of passengers at the departure platform on line *m*.
$F(x)$	=	Arrival distribution of passengers at the platform.
$P_{l-m,i,j}^{make}$	=	Number of passengers that make their planned connection to line *m* from vehicle *i* at stop *j* on line *l*.
$P_{l-m,i,j}^{miss}$	=	Number of passengers that miss their planned connection to line *m* from vehicle *i* at stop *j* on line *l*.
$N_{l-m,i,j}^{trans}$	=	Number of passengers transferring from line *l* to line *m* in vehicle *i* at stop *j*.
$P\left(t_{l-m,i,j}^{platform} \leq D_{m,i,j}^{act}\right)$	=	Probability that a passenger arrives at the departure platform before the departure of vehicle *i* on line *m*.

The passenger arrival time at the departing platform (Equation 4) will be the actual arrival time of the vehicle on line *l* plus the necessary walking time, assumed to be 2 minutes.

Now that the transferring passengers are divided into four groups, additional travel time for each individual passenger is:

$$T_{\downarrow}(l-m,i,j)^{\uparrow}(add,transfer) = \{\blacksquare(D_{\downarrow}(m,i,j)^{\uparrow}act - D_{\downarrow}(m,i,j)^{\uparrow}sched\&for\&\text{"Make } \mathbf{M}\text{:} \quad (5)$$

The total additional travel time for a specific transfer is:

$$T_{l-m}^{add,transfer,total} = \sum_{i} T_{l-m,i,j}^{add,transfer} \times N_{l-m,i,j}^{trans} \quad (6)$$

And the average additional travel time for a specific transfer is:

$$T_{l-m}^{add,transfer} = \frac{T_{l-m}^{add,transfer,total}}{N_{l-m,i,j}^{trans}} \quad (7)$$

where:

$T_{l-m}^{add,transfer,total}$	=	Total additional transfer time for passengers transferring from line *l* to line *m*.
$T_{l-m}^{add,transfer}$	=	Average additional transfer time per passenger for passengers transferring from line *l* to line *m*.
$T_{l-m,i,j}^{add,transfer}$	=	Total additional transfer time for passengers transferring from line *l* to line *m* from vehicle *i*.
$N_{l-m,i,j}^{trans}$	=	Number of passengers transferring from line *l* to line *m* from vehicle *i*.
$N_{l-m,j}^{trans}$	=	Total number of passengers transferring from line *l* to line *m*.

Reliability buffer time is calculated from the distribution of the individual additional travel times, as shown by Equation 7.

$$RBT^{transfer} = T^{add,transfer,95th} - T^{add,transfer,50th} \quad (8)$$

This framework is used to calculate reliability in a hypothetical network in Section 4 and in a case study in Section 5.

3.2 Variables leading to travel time variation for transfer passengers

There are 5 major variables that play an important role in the travel time distribution of transferring passengers. They are:

1. Variation of the distribution of vehicle arrival and departure times
2. Transfer walking time
3. Scheduled transfer time
4. Scheduled headways on both lines
5. Number of passengers at the given transfer

These variables are summarized in Table 1 along with their causes and effects.

TABLE 1 Causes and Effects of the 5 Important Variables in the Reliability of Transfers

Cause	Variable	Effect
Schedule/Network Design	Headways at transfer	Larger headways increase the magnitude of the negative effect of a missed transfer.
Schedule/Network Design	Scheduled transfer time	Longer leads to more scheduled travel time but a lower probability of missing a transfer.
Punctuality at transfer point Slack in schedule Distance of transfer point along line Location of holding point	Variation (Standard deviation) of vehicle arrival/departure times	Less variation on one or both lines can increase reliability
Transfer Point Layout Behavior of travelers	Transfer walking time	Less walking time means scheduled transfer time can be smaller
Demand patterns Quality of service	Number (or percent) of transferring passengers	Increases importance of a reliable transfer

A wider arrival time distribution of the first vehicle leads to more chances that the connection will be missed and the passenger will experience an additional headway of additional travel time. A wider departure time distribution of the second vehicle leads to more chance that the departing vehicle will depart before the passenger arrives at the platform, increasing the number of passengers that miss the connection.

The departure time distribution of the first vehicle has an impact when passengers arrive at their first vehicle according to the schedule, as in the long headway case. A wider distribution leads to more passengers missing their first vehicle, increasing the overall average travel time.

A shorter transfer walking time means that the scheduled transfer time (from scheduled arrival of the first vehicle to scheduled departure of the second vehicle) can be shortened by the same amount with no change in reliability.

Varying the scheduled transfer time leads to a change in the amount of passengers that make or miss their intended connection, and will have an effect on the distribution of passenger travel times. A tighter scheduled transfer time results in a greater chance of passengers missing the connection, while a longer scheduled transfer time results in a greater chance of passengers making their intended connection.

The scheduled headways of both vehicles have an impact on the final travel time distribution. The headway of the second vehicle is particularly important because it represents the consequence of missing the connection.

Finally, the proportion of transferring passengers on each specific transfer plays a role in the overall impact. A transfer with a higher proportion of passengers will contribute more to the total additional travel time of the system.

4. RESULTS OF HYPOTHETICAL NETWORK CALCULATIONS

The method introduced in the previous sections was tested in a hypothetical network that consisted of a tram line and a train line, both operating in two directions. Section 4.1 describes the test network and Section 4.2 presents the results.

4.1 The Network

The tram line consisted of 30 stops, with a 60 minute scheduled running time in each direction. The train line consisted of 5 stops with a 40-minute total running time in each direction. The train schedule included 1 minute of scheduled dwell time, or one minute of difference between the scheduled arrival and departure. 15-minute headways were used on both lines. Train schedules were set so that trains departed from the transfer point at the same time in both directions. Actual arrival and departure times were generated from cumulative running times on each link based on a random sample from a normal distribution with a standard deviation of 20% of the running time. The transfer point was located at the middle of the train line, but slightly off the middle of the tram line (stop 18 in one direction and 13 in the other). This is designed to be representative of a Dutch city, where the central train station is often just on the edge of the city center.

Passenger flows on the tram line were based on a hypothetical line used in (*1*). Two-thirds of passengers boarded in the first half of the line, in increasing amounts between the end of the line and the center. One-third of passengers boarded in the second half of the line, in decreasing amounts between the center of the line and the end. Passenger flows on the train lines were flat, with boardings and alightings equal at each stop. Transferring passengers were added to these numbers based on a percentage of the direct tram passengers (Figure 4).

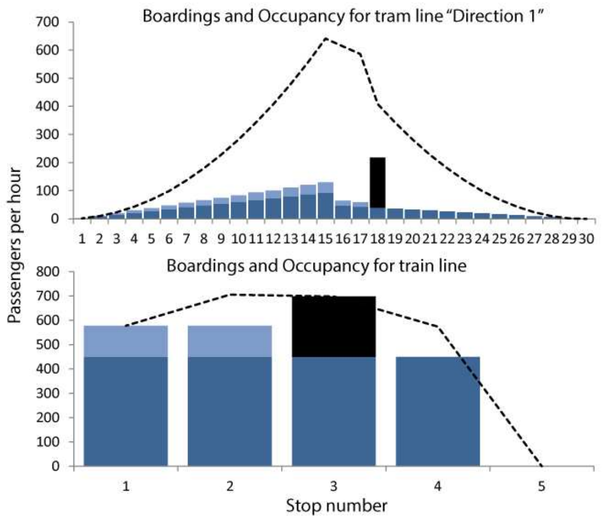

FIGURE 4 Boardings and occupancy for one direction of the tram line and the train line, showing the split between direct passengers and transferring passengers. Boardings are divided into passengers that board and will transfer, passengers that have transferred and passengers that do not transfer.

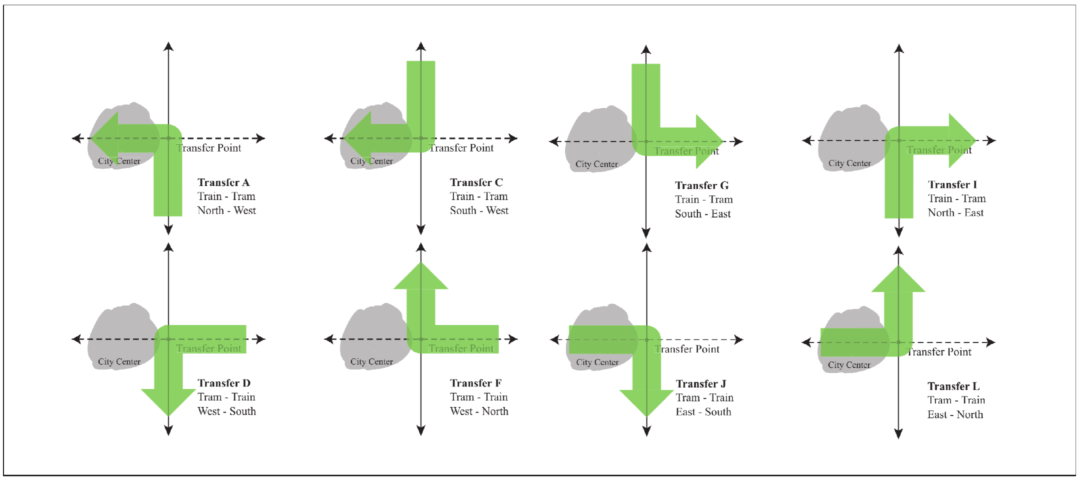

FIGURE 5 Identification of transfers and network used in hypothetical and real data cases. The train line is in bold, while the tram line is dashed. Specific transfer groups are identified by letters and are referred to as such in the text.

This network includes eight possible transfers: four from the tram to the train and four from the train to the tram (Figure 5). Because the train schedules are aligned, it is possible to choose the scheduled transfer time for four of these transfers, by shifting the tram line schedules. The transfer time of the four 'opposing' transfers is then set, and is not able to be chosen. This represents the most optimal case, because the maximum amount of transfers can be chosen. Scheduled transfer time is represented as the difference between the scheduled arrival time of the first line and the scheduled departure time of the second line. This does not include the walking time, so passengers would not be able to make a scheduled transfer of 1 minute, because of the 2 minute walking time.

In these calculations, the tram schedules are varied so that the scheduled transfer time ranges from 1 to 14. Calculations are done such that passengers are expected to make their transfer as scheduled. This means that most passengers will miss the 1 minute transfer, unless first line vehicles arrive early or second line vehicles depart late.

4.2 Results

The average additional travel time per passenger and the reliability buffer time for two specific transfers are shown in Figure 6. In both cases, these graphs are representative of all four similar transfers, since the main variables are the same for each case.

As expected, the results show that a transfer is more unreliable if the scheduled transfer time is less. This shows an important trade-off regarding reliability at a transfer. Increasing the scheduled transfer time lowers the additional travel time and reliability buffer time, but directly leads to increased overall scheduled travel time. For a single transfer, a reliability improvement comes at the expense of increased travel time.

A difference can be seen in the shape of the curves in these two examples. The tram to train transfer descends more steeply than the train to tram, but does not get as close to zero. The difference between the two is that in transferring to the train, vehicles are not allowed to depart ahead of schedule. This means that fewer passengers miss their connections in tight transfers, because the connecting vehicle cannot depart early. For long transfer times, the average additional travel time does not approach zero, because early departures are not allowed on the train lines.

Two things can be noted about the reliability buffer time. In the train to tram transfer, the 95th percentile of travel times drops steeply from around 15 minutes, to around 3 minutes. It would appear that there is a big gain in reliability from moving the scheduled transfer time from 8 minutes to 9 minutes. This is misleading because of the nature of reliability buffer time. The distribution of passenger transfer times is actually made up of two groups, one of which is clustered around 0, for passengers that make their connection and another which is clustered around the headway of the connecting service, for passengers that miss their transfer. The 95th percentile of this distribution stays around 15 when the percentile is in this upper sub-distribution, but appears to drop quickly because there are few passengers with in between transfer times.

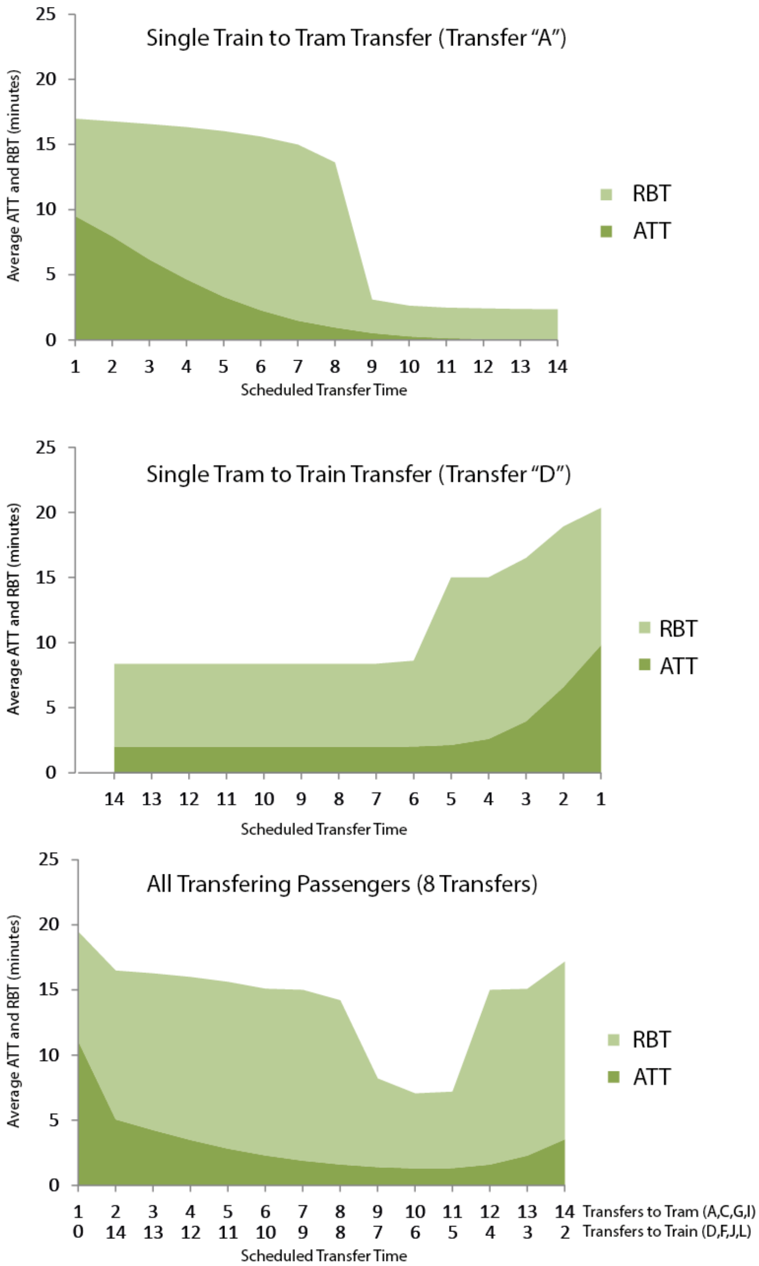

FIGURE 6 Average additional travel time and reliability buffer time for passengers of "Transfer A" (top), passengers of "Transfer D" (middle) and all transferring passengers (from all 8 transfers, bottom).

The tram to train transfer has some reliability buffer times that are well above the 15-minute range. These result from additional travel times for passengers who miss both their first vehicle and their connection. This part of the distribution was not seen in Transfer A because of the nature of the calculation model. Transfer A passengers originate on the train line. Since the train does not depart early, and passengers are assumed to make their vehicle if it departs any time after τ^{early}, it is impossible for passengers to miss their connection when originating on the train line. This is a shortcoming of this assumption.

Because varying one transfer has an opposite effect on another transfer, it is interesting to look at the effects of all transfers together. Figure 6 (bottom) shows the average additional travel time and reliability buffer time for all 8 groups of transfer passengers, while varying the scheduled transfer time of all 8 transfers. The optimal point, in this case, is a 10-minute scheduled transfer time for train-tram transfers and a 6-minute transfer time for tram-train passengers.

The optimal point is located towards the side of the graph where tram-train transfer passengers have a tighter connection. The primary reason for the skew in this direction is, that the train does not depart early, meaning tighter connections in that direction are more reliable.

This gain in reliability comes at the cost of increased scheduled travel time. As can be seen in Figure 6, the relationship of the two depends on circumstance. A steeper additional travel time slope indicates more reliability gains for an equal amount of increased travel time. For example, in Transfer D, increasing the scheduled transfer time by one minute causes a gain in reliability if the new transfer time is below 5 minutes, but there is no change in reliability if the scheduled transfer time was increase from 8 minutes to 9 minutes. However, merely optimizing the reliability may come with the cost of increased scheduled travel time. More direct numerical attention is paid to this in the real network example. More insights into this trade-off are provided in (*9*).

5. REAL NETWORK EXAMPLE

The hypothetical network example was used to illustrate the important factors surrounding reliability at a transfer point. However, this method was designed to analyze real data. Here, an example is presented that shows how AVL and passenger count data can be used with the calculations presented in section 3, and how transit operators can use the results.

Scheduled and actual arrival times and departures as well as passenger flows were provided by the HTM for tram line 9 in The Hague, Netherlands. This example examines the transfer at the Den Haag HS station. The train schedule was used as input to the model, while actual train departure and arrival times were generated using a log-normal distribution, with parameters set to mimic the on time performance of the Dutch railways (NS).

Data was used for weekday evening hours over a period of 8 days in November 2012. In this case both services have 15-minute headways.

While holding the train schedule constant, the westbound direction of the tram schedule was varied in order to filter through all of the possible scheduled transfer times. The effects on additional travel time are shown in Figure 8. In this case, four transfers are affected by this shift. These transfers include transfers from the westbound tram line to both train directions, and both train directions to the westbound tram line. These transfers are labeled as G, I, J and L in Figure 5. Also shown is the average additional travel time for all 8 groups of transferring passengers, which also includes the constant ATT from the four other transfers. The average additional travel time for all passengers in the network, including direct train and tram passengers, shows that the number of transferring passengers has a big impact when considering all passengers.

Because, in this case, the trains do not depart at the same time in both directions (as they did in the hypothetical example), the unreliability "peaks" do not align, meaning that it is difficult to find a schedule for this direction of the line that is reliable for all transfers.

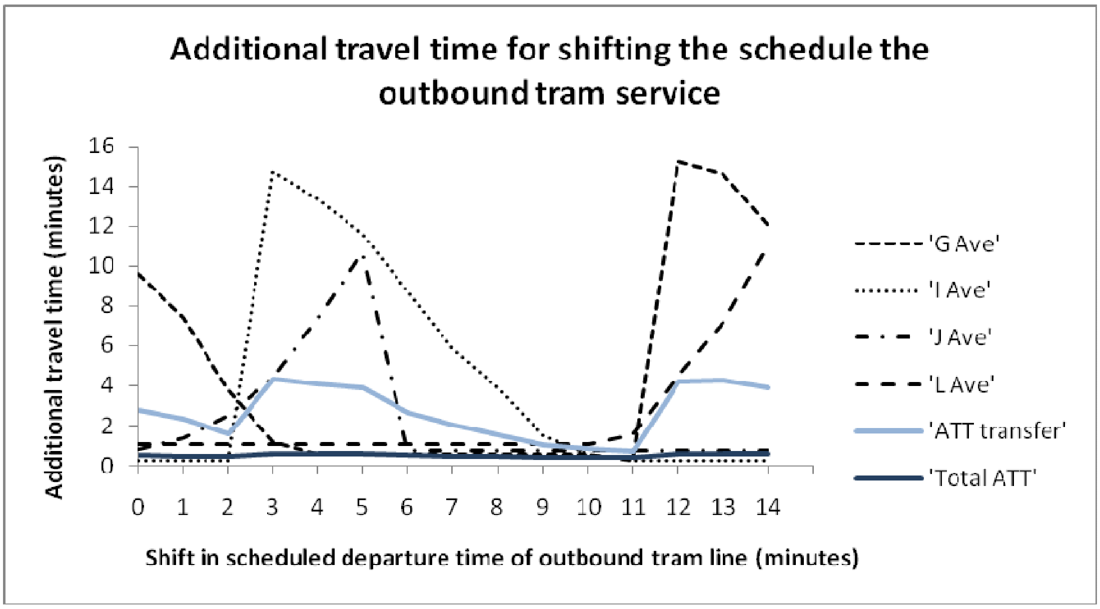

FIGURE 7 Additional travel time for shifting the schedule of tram line 9 (westbound) in Den Haag. The transfer point is Den Haag HS.

The most optimal point requires shifting the schedule 11 minutes, changing some scheduled transfer times by 11 minutes and some by 4 minutes. This change results in a change in scheduled travel time for these passengers. Table 2 shows that increasing the scheduled transfer time, and thus the scheduled travel time, leads to a decrease in additional travel time and reliability buffer time and a more reliable service. The opposite is also true, the change for Transfer L reduces the scheduled travel time by 11 minutes, but increases additional travel time and reliability buffer time. For Transfer I, there is no change in reliability because the original and new transfer times are large enough that reliability is not affected. This result demonstrates that a synchronization of one transfer, for a more reliable service, may cause other transfers to become less reliable.

TABLE 2 Per Passenger Changes in Scheduled Travel Time and Reliability for an 11 minute shift in the schedule of tram line 9 (westbound)

	Change in:		
	Scheduled Transfer Time	Additional Travel Time	Reliability Buffer Time
Transfer G	11.00 min	-9.33 min	-0.95 min
Transfer I	-4.00 min	0.00 min	0.00 min
Transfer J	4.00 min	-0.05 min	-0.20 min
Transfer L	-11.00 min	0.51 min	6.16 min

A transit operator must choose which transfer to synchronize, choose the optimal point for reliability at a transfer point, or the optimal point for the trade-off of reliability and travel time. Here the number of passengers going through each transfer is also important. A transfer with greater demand will have a greater impact on the overall average additional travel time.

6. CONCLUSIONS

This paper has presented an extension of the Van Oort (*1*) reliability calculation model to account for transfers for long headways services. The model considers each transferring group separately at a transfer point involving 8 possible transfers. This allows the losing and winning transferring groups to be identified. The optimal transfer time, for reliability, is dependent on the distributions of the actual vehicle arrival times, the transfer walking time, the headway and the number of passengers making a transfer. It was shown that the departure restrictions also have an effect. Tighter transfers are more reliable for passengers traveling to the train service because the train vehicles do not depart early.

For a single transfer, an important trade-off exists between scheduled travel time and additional travel time due to unreliability. The optimal value of this trade-off is related to the specific characteristics of the transfer, including actual vehicle distributions and headways of both lines as well as transfer walking time and transfer demand.

However, changing the schedule of one direction of one line, in order to optimize a single transfer, can directly affect three other transfers. Here, a transit operator has a choice to focus on a specific transfer group, while neglecting others, or to pick an optimal point that may cause travel time and reliability costs and benefits to differing passenger groups.

This method described in this paper can be applied for cost benefit analysis, and can be used to identify the total benefits to passengers for a reliability improvement, as well as the benefits that are given to specific passenger groups.

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