LINE LENGTH VS. RELIABILITY: NETWORK DESIGN DILEMMA IN URBAN PUBLIC TRANSPORT

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ABSTRACT

Unreliability of public transport is a well-known problem. During the design stages of public transport, little attention is paid to operational reliability, although many design choices have a great impact on schedule adherence. During the network design, reliability should be taken into account as a design parameter. This paper deals with line length. A new design dilemma is introduced: length of line vs. reliability. Long lines offer many direct connections, thereby saving transfers. However, the variability is often negatively related to the length of a line, leading to less schedule adherence and additional waiting time for passengers. This paper suggests taking into account both the positive and negative effects of extending or connecting line . A tool is developed to calculate the additional waiting time due to variability and transfers based on actual journey and passenger data. A case study in The Hague shows that in the case of long lines with large variability, splitting the line could result in less additional travel time because of improved reliability. This benefit compensates for the additional transfer time, provided that the transfer point is well chosen. This research shows the effect of when the transfer point is chosen at stop with many and fewer passing travelers. The latter could lead to a decrease of about 30% in additional waiting time. Splitting a long line into two lines with an overlap in the central part could even result in more time savings. In that case, fewer travelers have to transfer.

1. INTRODUCTION

Many characteristics of urban public transport influence mode choice of passengers. Price, image and comfort are examples. One of the most important aspects is travel time: the time a traveler needs to arrive at his destination. The speed of the vehicle greatly influences the travel time, but is not the sole factor. A large part of an urban public transport journey is waiting time at the stop and transferring. Variability in driving times influences this waiting time, as is stated in (*1*). Large variability decreases schedule adherence and thus reliability of the transport service.

Improving the reliability of public transport is an important research subject. Much research is executed on how reliability can be improved during operations. Examples are: priority at traffic lights, holding and dispatching strategies (e.g. *2,3,4,5*) and control systems (e.g. *6, 7*).

During the design stages of public transport, less attention is paid to reliability of operations, although a lot of design choices have a great impact on schedule adherence (e.g. *1,8)*. Both during the network and timetable design reliability should be taken into account as a design parameter.

This paper deals with the design parameter line length. In the Netherlands, there has been increased focus on connecting lines. An example of such a connection is RandstadRail (*6*). This new light rail system replaces and connects two tram lines, two former heavy rail lines and one metro line. The added value of these new links is a more direct connection from origin to destination. Passengers do not have to transfer anymore to reach the city centre, for example, which saves much time. But when a line is extended there is a chance of an increase in variability and thus unreliability of transport services. This could lead to additional travel time. During the design process, it is important to take both the effects of extending or connecting lines into account: both the time savings as well as the possible additional travel time due to larger unreliability. This design dilemma is analyzed in this paper in a quantitative way, using a tool calculating additional travel time for passengers due to unreliability and transfers.

2. NETWORK DESIGN

2.1 Network dilemmas

The network design of urban public transport consists of two parts: the infrastructure design and the service network design. Especially in rail networks these designs are heavily connected. In this research the focus is on service networks: the network of public transport lines.

The following main variables for the network design can be distinguished (*9,10)*:

- Line density
- Stop density
- Frequency

Line density is the total length of lines in a certain area. This determines the coverage of public transport. The stop density is the number of stops in a certain area. The more stops, the shorter the distance from origin to the stop is, but the slower the system will be. The last important aspect is frequency; the number of trips during the day. This determines the availability in time of public transport.

In (*10)* is shown that the above criteria lead to some network design dilemmas, when a design is made with fixed costs. These dilemmas are:

- Stop density vs. driving time
  The more stops there are, the shorter the access time to a stop will be. However, the operational speed of the system will decrease.
- Frequencies vs. line density
  Designing more lines implies a lower frequency on these line compared to a network with less lines.

One dilemma, which is missing is the dilemma of line length vs. reliability. Van Oort stated in (*11*) that there is a positive relation between line length and variability of driving times. This variability leads to unreliability. Figure 1 shows the standard deviation of driving time as a function of the distance for all bus and tram lines in The Hague. During a month one morning peak hour trip is analysed. As to be expected, the distribution increases with the length of the line. The increase in deviation for the bus lines is greater compared to the tram lines. Contrary to tram lines the distribution of travel times of bus lines sometimes decreases. This is because of operational measures like holding vehicles ahead of schedule at a stop. Despite these measures, the distribution of driving times of bus lines is still greater than that of tram lines. This is probably because of the less proportion of buses having their own right of way. For the tramlines the average increase of the standard deviation is 11,1 s/km. For bus this increase is even larger: 17,6 s/km.

Variability of driving times leads to poor schedule adherence and longer travel times for passengers. Research (*11)* shows the relation between variability in driving times of vehicles and travel times of passengers. It is illustrated that poor schedule adherence could lead to an average of over 3 minutes additional travel time per passenger of a line. In urban public transport, most journeys are short, so this additional waiting time could lead to 25% additional travel time for the total journey, regardless of the perception of passengers of waiting vs. driving.

2.2 Line length vs. reliability

The former paragraph introduced a new network design dilemma: line length vs. reliability. Long lines tend to be less reliable so at the moment of designing these lines it would be interesting to take this explicitly into account. Designing shorter lines or splitting existing ones could be a solution. However, the effect of that choice is that fewer direct connections are offered, which means additional transfers and thus additional travel time. The question which will be answered in this paper is: What is the effect of splitting public transport lines into two parts on travel times, taking into account the effect of variability and an additional transfer?

Figure 2 illustrates the effect of decreasing line length. Line 1 operates from A to B. The variability of driving time increases along the line. Line 2 is the same line as line 1, but this line it is divided into two parts: From A to C and from C to B.

Two main differences exist between line 1 and 2:

- The variability of line 2 is smaller
- Introduction of a transfer at C for line 2

The additional transfer will lead to additional travel time for passenger passing point C. The decrease in variability will lead to better schedule adherence and shortens additional waiting times for passenger traveling between C and B.

The trade-off between the additional transfer and better schedule adherence depends on the following variables:

- Travel patterns of passengers: the location of point C is important in terms of the former number of travelers traveling over C
- Frequency: Both the waiting time at C due to transferring and the waiting times at other stops depend on the frequency of the line
- The schedule adherence: additional waiting time at the stops depends on the deviation of the timetable

From an operator's point of view, splitting lines could lead to additional costs. This should be taken into account during design as well. This research only focuses on the passengers effects.

3. CALCULATION MODEL EFFECTS LINE LENGTH

To deal with the new design dilemma of line length vs. reliability, a tool is developed to calculate the average waiting time of all travelers on a line. This additional waiting time arises because of poor schedule adherence and transferring (in case of splitting the line). This tool uses of the following input:

- Actual data of driving times of trips
- Actual data of travelers boarding and alightening
- Frequency
- Location of transfer point

The first step in the model is to calculate schedule adherence at every stop. Formula 1 shows the formula to calculate punctuality:

$$\overline{p}_j = \frac{\sum_i \left| t_{i,j}^{real} - t_{i,j}^{planned} \right|}{n_i} \qquad (1)$$

where:

$\overline{p}_j$ =*average punctuality at stop j*
$t_{i,j}^{real}$ = *real departure time of vehicle i at stop j*
$t_{i,j}^{planned}$ = *planned departure time of vehicle i at stop j*
n_i = *number of vehicles*
j = *stop index*
i = *vehicle index*

Punctuality is a commonly used indicator of reliability, but does not take into account the difference between the effect of driving ahead of schedule or driving late. To consider this effect, the model computes the additional waiting time per traveler at a stop. Formulas 2-4 show the algorithms. Passengers are assumed to arrive between 2 minutes before and 1 minute after the scheduled departure and therefore they will not incur any additional waiting time if the vehicle departs in this time window (*12*). It is important to note that there is a difference between driving ahead of schedule and driving too late. Driving ahead leads to a waiting time equal to the headway. Especially in case of low frequencies, this means a large increase in waiting time. Driving late creates an additional waiting time equal to the delay.

The additional waiting time is first calculated per stop and afterwards it is computed as a weighted average for all passengers on the line, depending on the number of boardings per stops.

$$\begin{cases} ET_{i,j} = H, & \mathrm{p}_{\mathrm{i,j}} \leq -120 \\ Ei_{i,j} = 0, & -120 < \mathrm{p}_{\mathrm{i,j}} < 60 \\ ET_{i,j} = \mathrm{p}_{\mathrm{t,j}}, & \mathrm{p}_{\mathrm{i,j}} \geq 60 \end{cases} \quad (2)$$

$$ET_j = \frac{\sum_i ET_{i,j}}{n_i} \quad (3)$$

$$ET_{stop} = \sum_j \alpha_j * ET_j \quad (4)$$

where:
$ET_{i,j}$ = *additional waiting time due to vehicle i at stop j*
H = *scheduled headway*
$p_{i,j}$ = *deviation of vehicle i at stop j*
ET_{stop} = *average additional waiting time per passenger on the line*
α_j = *proportion of passengers boarding at stop j*

In the case of splitting the line into two parts, a transfer is introduced, leading to additional waiting time for passengers who want to pass this point. Formulas 5-7 show the related computation, including the calculation of the average effect for all passengers. At the transfer point the punctuality is set to zero and it develops as it did on this part of the route before splitting.

In the end all waiting times per stop are added, taking into account the number of passengers at a stop and the number of passenger who have to transfer. The result is the average additional travel time for all passengers on the line. This is calculated for the scenario of one long line and two short lines with a transfer point. This makes it possible to compare two scenarios and analyze the design dilemma of line length and transfers.

$$ET_{t\_p} = \frac{H}{2} \quad (5)$$

$$ET_{transfer} = \beta_{t\_p} * ET_{t\_p} \quad (6)$$

$$ET_{total} = ET_{stop} + ET_{transfer} \quad (7)$$

where:
ET_{t_p} = *additional waiting time due to transferring at transfer point*
$ET_{transfer}$ = *additional travel time per passenger due to transferring*
β_{t_p} = *proportion of passengers passing the transfer point*
ET_{total} = *mean additional waiting time per passenger on the line*

4. CASE STUDY: EFFECT OF SPLITTING LINES IN THE HAGUE

The approach described in the former paragraph is used for a case study conducted in The Hague. Actual data of driving times and the number of travelers are used to calculate the effect of splitting long lines into two parts. Line 1, a tram line of 20 km, is used as an example. At the end of this paragraph, additional results of other tram lines are given. Table 1 gives the main characteristics of the lines used in this case.

4.1 Case study tram line 1

As stated earlier, the pattern of boarding and alightening is of great influence in the case of introducing a transfer to improve overall reliability. Two examples of stops of line 1 illustrate the effect of this factor. In figure 3 the part of travelers who are passing a certain stop are given as a percentage of the total numbers of travelers. The stop “CT” (i.e. City Centre) has a percentage of 12% passing passengers, which means that 12% of all users of this line travel over this point. At the stop “He” (i.e. Heerenstraat) more passengers are passing. This part of line 1 is used by a large number of passengers, but not many are boarding or alightening here.

In this paragraph two computations are made of the mean additional waiting time per traveler if both stops are used to divide line 1 into two parts. The locations to split the line are chosen regarding the passing number of travelers or the division of the line in two equal parts.

4.1.1 City Centre as a transfer point

The first scenario is City Centre (“CT”) as a transfer point. This location is chosen, because many passengers exchange at this stop. The results of splitting are as shown in table 2. Figure 4 illustrates the effect of variability on additional waiting time per stop.

These figures show a large decrease of the additional waiting time at stops. The punctuality restores after the transfer location and so does the additional waiting time. Introducing a transfer leads to additional waiting time, but because of the small number of travelers making a transfer this effect is not great and is even smaller than the decrease in additional waiting time due to splitting.

4.1.2 Heerenstraat as a transfer point

Another possible transfer point is the middle of line 1. Splitting the line here divides the line in two equal parts. The results of splitting are shown in table 3.

These results show a decrease in waiting time at the stops: because the line length in the case of two lines is shorter, the variability does not reach high values, leading to less additional waiting time at stops. However, the introduction of the transfer will lead to more waiting time and because the number of passing travelers on this stop is high, many passengers will incur this transfer penalty. This additional waiting time due to transferring is not compensated by the benefit of a higher schedule adherence.

4.2 Analysis other lines

Similar to the calculations of line 1 above, an analysis is made of other long lines in The Hague. The results are shown in figure 5. The effect of splitting the lines differs per line, because of differences in travel patterns and punctuality characteristics. The additional waiting time due to transferring on line 15/16 is very small, because this line actually consists of two lines, which are connected to each other only because of efficiency, not to offer more direct connections. It can be seen that this efficiency measure increase the additional waiting time by 50%. The effect of splitting is positive for line 17 as well; the effect is about 30% less additional waiting time.

Although it was to be expected that splitting bus line 23 would decrease the additional waiting time as well, line 23 is by far the longest and least punctual line in The Hague, the effect of splitting is negative. Figure 6 shows the main reason for this effect: there is no ideal location for a transfer point on this line: the number of passing passengers on the main part of the line is never below 18%.

On line 23 there is no stop where enough passengers exchange. In this case, splitting the line with some overlap could be a solution, as figure 7 shows. Not splitting the line at C, but at D and E, with overlap between D and E. This way fewer direct connections are removed. It is clear though that this solution leads to more expensive operations due to the overlap. This adds a new dimension to the previously mentioned dilemma: the additional operational costs vs. the additional reliability benefits. Additional research is needed on this topic. The calculation model presented in this paper is to be adjusted to assess the effects of this.

5. CONCLUSIONS

This paper describes research on network design of urban public transport, taking reliability explicitly into account. An additional design dilemma is introduced: the length of line vs. reliability. Long lines offer many direct connections, thereby saving transfers. However, the variability is often negatively related to the length of a line, leading to less schedule adherence and additional waiting time for passengers. This paper suggests taking into account both the positive and negative effect of extending or connecting lines. A tool is developed to calculate the additional waiting time due to variability and transfers based on actual journeys and passengers' data. A case study conducted in The Hague shows that in the case of long lines with large variability, splitting the line could result in less additional travel time due to improved reliability. This advantage compensates the additional time of transferring if the transfer point is well chosen. This research shows the effect when the transfer point is chosen at a stop with many and fewer passing travelers. The latter could lead to a decrease of about 30% in additional waiting time. Splitting a long line into two lines with an overlap in the central part could even result in more time saving. In that case, fewer travelers have to transfer.

The analysis in this paper illustrates that there are opportunities to increase the level of reliability in urban public transport by adjusting the design of the network as well as timetable planning. HTM and Delft University of Technology continue their research on these topics to achieve a better way of planning of urban public transport which results in a higher level of reliability.

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LIST OF TABLES

LIST OF FIGURES

TABLE 1 Characteristics of Lines used in the Case Study

Line	Direction	Length [km]	Headway [min]
Tram 1	Delft	20	10
Tram 15/16	Moerwijk	17	10
Tram 17	Wateringseveld	16	10
Bus 23	Kijkduin	29	10

Data gathered from March 2006, working days, during day hours (9 a.m. - 4 p.m.) (13)

TABLE 2 Additional Waiting Time per Passenger due to Variability of Driving Times and Transfers for Line 1 (Transfer at City Centre)

Scenario	Mean waiting time [s]	Waiting time at stops [s]	Transfer waiting time [s]
Line 1 Reference	100	100	0
Line 1 Two Parts	73	36	37

TABLE 3 Additional Waiting Time per Passenger due to Variability of Driving Times and Transfers for Line 1 (Transfer at Heerenstraat)

Scenario	Mean waiting time [s]	Waiting time at stops [s]	Transfer waiting time [s]
Line 1 Reference	100	100	0
Line 1 Two Parts	172	65	107

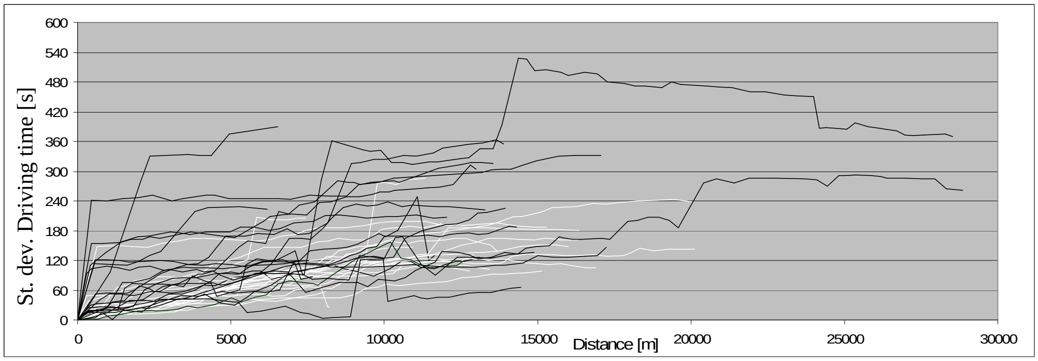

FIGURE 1 Standard Deviation of Driving Times [s] (white= Tram Lines; black= Bus Lines)

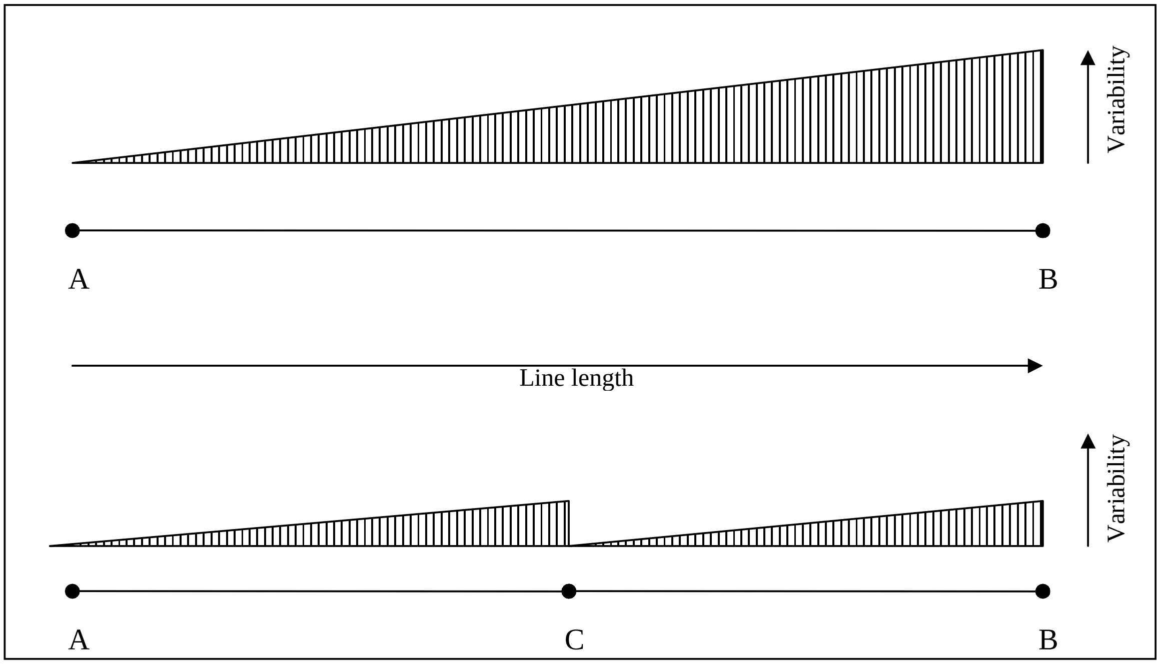

FIGURE 2 The Effect of Splitting a Line (at C) on Variability

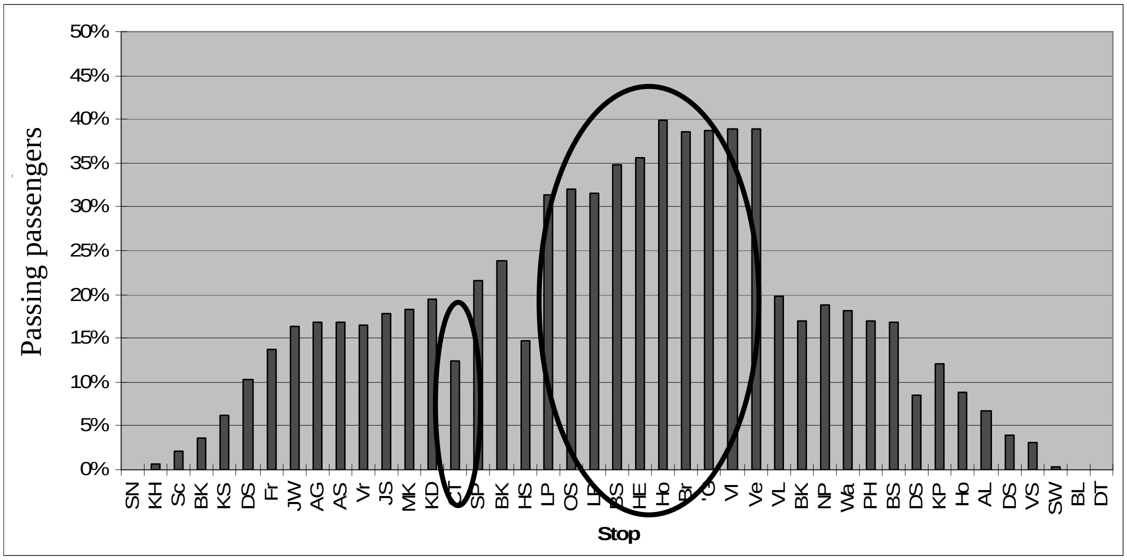

FIGURE 3 Number of Travelers Passing a Stop as a Percentage of Total Boardings on Tram Line 1

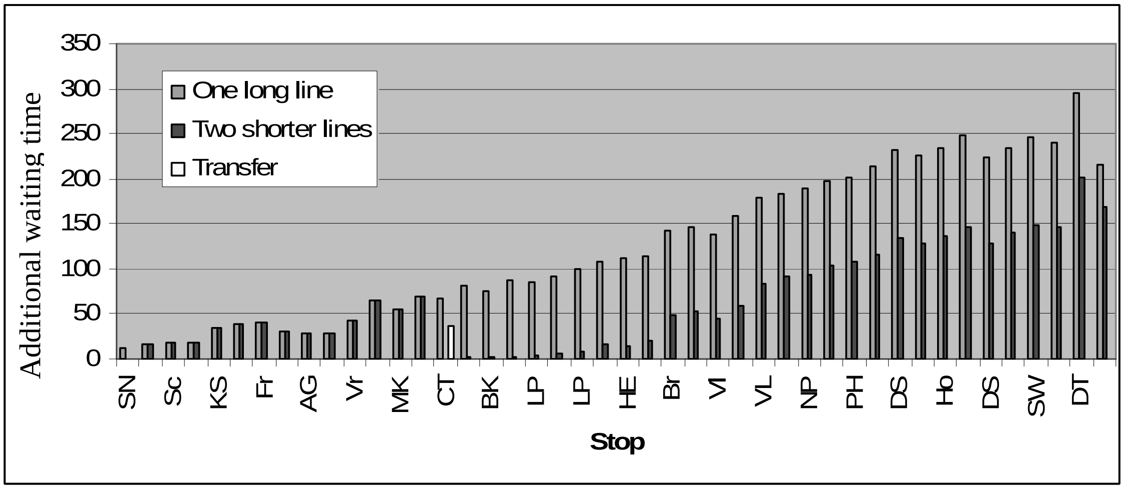

FIGURE 4 Additional Waiting Time per Passenger due to Variability of Driving Times and Transfers per Stop of Line 1

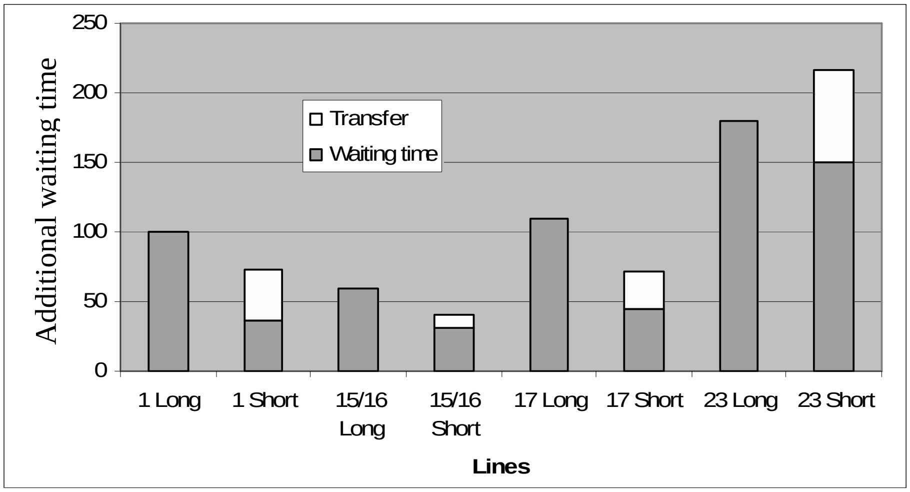

FIGURE 5 Effect of Splitting Lines on Mean Additional Waiting Time per Passenger

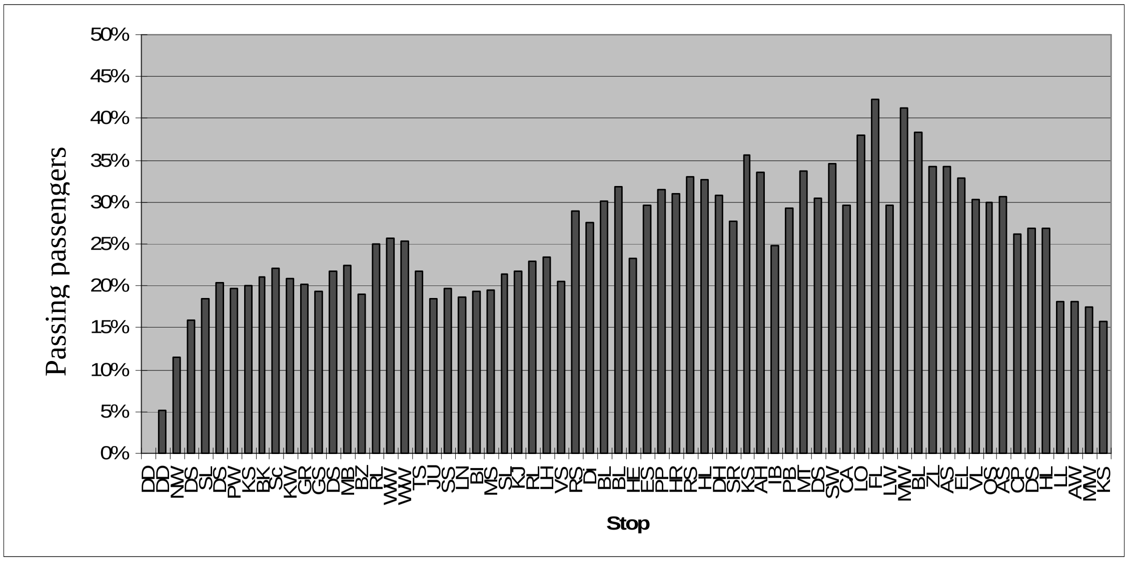

FIGURE 6 Number of Travelers Passing a Stop as a Percentage of Total Boardings on Bus Line 23

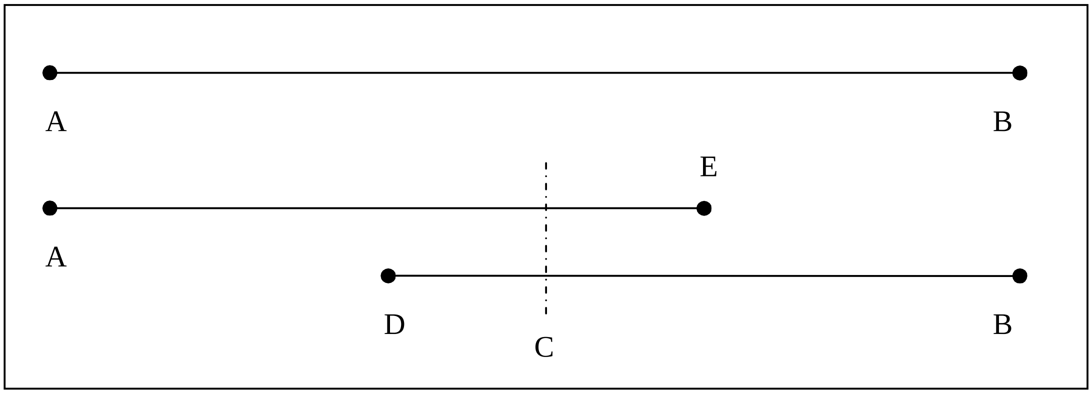

FIGURE 7 Splitting a Line into Two Parts with an Overlap