THE IMPACT OF RAIL TERMINAL DESIGN ON TRANSIT SERVICE RELIABILITY

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ABSTRACT

Ensuring reliable rail transit services is an important task for transit agencies. This paper describes research of the effects of various terminal configurations on reliability of services. Besides terminals, the results could also be used for short turning infrastructure. Short turning is a very widespread measure to restore service after major disturbances and in many rail networks, additional switches are constructed to enable short turning.

In this paper, it is suggested to consider reliability already during infrastructure design and the mechanisms and effects of infrastructure design are shown. Calculations of the average delay per vehicle, regarding three main types of terminals, show the effect of frequency on the one hand and occupancy time (determined by the distance from the switches to the platform (i.e. length of the terminal), technical turning time and scheduled layover time) on the other. The substantial effect of arrival variability and the number of lines using the terminal is illustrated as well. It is shown that using stochastic variables, delays will occur, although they are not to be expected in the static case. The best performance regarding reliability is achieved, when double crossovers are situated after the platforms. Single tailtracks facilitating the turning process are only acceptable if frequencies are low. Although, , they are often used in practice as short tuning facility for high frequent services. This research shows the large impact of occupancy time on expected delays. It is recommended to minimize this time by designing short distances between switches and platform and tailtracks.

Capacity management is not common use in transit. However, increasing frequencies and large deviations force to consider limited capacity, while planning infrastructure. If not, delays will occur and additional measures are necessary to solve them. This could be more expensive in the long run.

1. INTRODUCTION

Ensuring reliable rail transit services is an important task for transit agencies. This paper focuses on service reliability: matching the actual performance with the schedule. Attention for transit quality and efficiency in general and reliability in particular is increasing. Recent development and improvement of automated vehicle location (AVL) and automated passenger counting (APC) systems enable detailed research (as shown by e.g. *1,2,3,4*). Additionally, IT applications remove barriers to implement measures to improve reliability (e.g. computer aided dispatching systems, as described by (*5,6,7*)). In literature, several options are presented to improve reliability (e.g. holding (*8*), conditional priority (*9*), coordination of services (*10*) and slack allocation (*11*)). Much attention is paid to operational measures (e.g. *5,12*). Both in literature and in practice, little effort is devoted to the correlation between infrastructure configuration and reliability, although a high level of reliability never could be achieved without a proper design of terminals, stops and junctions. In (*13*) is stated that with increasing ridership and rising expectation on rail service quality, terminal capacity and performance have become a major concern for transit agencies. Research on the effect of terminal configuration on quality of service is presented, but the results are limited to only one type of terminal. It also concludes that there is a lack of well–established concepts and tools in the existing rail transit literature that a transit agency can use to assess capacity and performance of heavily utilized rail terminals. In (*14*), interesting results on capacity assessment are shown as well. However, this focus is on junctions. In (*15*) is elaborated on capacity in urban rail transit too, showing a case from Copenhagen.

This paper describes research of the effects of various terminal configurations on reliability of services, based on simulation studies. Besides terminals, the results could also be used for short turning infrastructure. This infrastructure enables service restoration if a part of the infrastructure is temporally unavailable (as described by (*16)*). The main variables are the number and locations of switches and the number of available tracks. Besides schedule variables, frequency, layover time and the crew relief process are of importance as well.

2. SERVICE RELIABILITY IN TRANSIT

2.1 Measuring Reliability

Within the transit industry, punctuality (i.e. average schedule deviation) is a commonly used indicator to present the level of reliability. Another often used one is the percentage of vehicles experiencing a schedule delay within a bandwidth (e.g. between 1 min. early and 3 min. late). In high-frequency systems, more focus on headway deviation is common, while travelers tend to arrive at random (*10*). Although these variables give an impression of service performance and reliability, the main focus is on the vehicles. The perception of the passengers is not explicitly measured by these indicators. More focus on passengers' effects is needed (see e.g. (*17*)). To measure the perception of passengers explicitly, the additional travel time, due to unreliability is a proper indicator (*7,18*). Using actual performance and actual passengers' data, the effect of unreliability could be calculated, comparing the actual performance with the 100% regular service. In (*3,19*) is stated that besides the average travel time, the 95-percentile value of travel time should be taken into account as well, while passengers have to budget for this time. They experience this travel time about once per month, and if they don't want to be late at their destination, they have plan this time and budget it. This additional time is called Reliability Buffer Time (RBT).

2.2 Calculating Reliability

As stated before, the additional travel time and RBT could be calculated if actual performance and passengers' data is available. Equation 1 is used to calculate the deviation of the timetable. Equations 2-3 enable calculating the effect of schedule adherence on additional travel time. Both the average waiting time and the RBT are calculated. This research focuses on situations where passengers arrive randomly at the stop. If passengers arrive at random at the stop, even headways are important, thereby minimizing the waiting time (*20*). Equations 4 and 5 are used to calculate the average waiting time per passenger on the line, where the number of boardings per stop is taken into account to achieve a weighted total. Equation 6 adds the RBT and average value, using weights (relative to in-vehicle time).

$$p_{i,j} = D_{i,j}^{actual} - D_{i,j}^{sched} \qquad (1)$$

$$T_j^{waiting} = \frac{H^{sched}}{2} * (c_v (H_j^{actual})^2) \qquad (2)$$

$$RBT_j^{waiting} = T_{i,j}^{95\% waiting} - T_j^{waiting} \quad (3)$$

$$T^{waiting} = \sum_j \alpha_j * T_j^{waiting} \quad (4)$$

$$RBT^{waiting} = \sum_{j=1}^{n_j} \alpha_j * RBT_j^{waiting} \quad (5)$$

$$T^{add} = \theta_{stop} * T^{waiting} + \theta_{RBT} * RBT^{waiting} \quad (6)$$

where:

$p_{i,j}$	= punctuality of vehicle i at stop j (reference case)
$D_{i,j}^{actual}$	= real departure time of vehicle i on stop *j* (reference case)
$D_{i,j}^{sched}$	= planned departure time of vehicle i on stop *j*
i	= trip number
j	= stop number
$T_{i,j}^{waiting}$	= additional waiting time due to vehicle i at stop j
$RBT_j^{waiting}$	= Reliability Buffer Time at stop j
T^{add}	= average additional waiting time per passenger
H^{sched}	= scheduled headway
H^{actual}	= actual headway
c_v	= coefficient of variation
α_j	= proportion of passengers boarding at stop j
θ_{stop}	= relative perception of waiting time
θ_{RBT}	= relative perception of Reliability Buffer Time

2.3 Effect of Punctual Departure at Terminal

A key priority for transit agencies is on-time departure at the terminal. Earlier research stated that the punctuality at the terminal ($p_{i,1}$) greatly affects the additional travel time of all travelers on the line (*7*). A case study is performed in The Hague in The Netherlands to assess the effect of departing on time from the terminal on additional travel time. Equations 7 and 8 are used to assess the effect of punctual departure on schedule adherence on the complete line. A new punctuality is calculated for all stops, adjusted for punctual departure.

$$D_{i,j}^{actual\_new} = D_{i,j}^{actual} - p_{i,1} \quad (7)$$

$$p_{i,j}^{new} = D_{i,j}^{actual\_new} - D_{i,j}^{sched} \quad (8)$$

where:

$D_{i,j}^{actual\_new}$	= actual departure time of vehicle i on stop *j* (new case)

After the recalculation of the punctuality of all trips and stops, a new additional travel time is calculated, using equations 2-6. This model assumes that the change in punctuality along the whole line is only affected by the punctuality change of the first stop. This will lead to an underestimation of the new effect: in real time the effect of bunching will increase an initial deviation, as described by (*21*). Despite this underestimation, the model is able to clearly illustrate the importance of punctual departure.

For several tram lines in The Hague, it is calculated what the decrease of additional travel time per passenger (including RBT, see equations 2-6) is when departure punctuality would be 100%. The characteristics of these lines are given in table 1 and figure 1 shows the results. Actual passengers' and trip time data of April 2007 (AM peak) are analyzed, using the TriTapt tool (*22*). The differences between lines are caused mainly by varying actual punctuality characteristics of the line.

Figure 1 clearly shows that departing on time could lead to large travel time reductions. Traditionally, such a finding leads to the conclusion that driver discipline should be enforced; however, for rail bound public transport the design of the terminal infrastructure plays an important role as well, besides proper timetable design. The next paragraph explores the effect of the design of terminals and the impact on reliability.

3. TERMINALS TYPES AND CHARACTERISTICS

Rail terminals could be designed in many ways: hundreds of types exist over the world. The key design variable is whether to choose a loop or a stub-end. Although loops require a lot of space, most of the time their capacity is larger than stub-end terminals (*13,14*). When bi-directional vehicles are used and space is lacking, a stub-end terminal is frequently chosen. The main benefit of this type is that it does not require much space. The disadvantage compared to loops is that capacity is limited, which could lead to delays.

Figure 2 shows the three most popular types of stub-end terminals and the processes at these terminals. They have zero, one or two tail tracks. These types are analyzed in this research. Type A enables turning before the platform, the other two after the platform. At type A, the vehicle arrives at and departs from the same track, while at type B and C these two actions are performed at different platforms. Note that besides the double crossovers illustrated in figure 2, universal crossovers are often designed as well. The difference with double crossovers, in terms of capacity, is that the driving times necessary to proceed from the switch to the platform differs per track. But in general, this is only a few seconds (if the crossovers are located close to each other). Besides enabling the turning process, terminals could also be used for parking vehicles. One vehicle could be parked at type A, although still only one track could be used for the turning process and capacity would drop. At type B, no parking is possible without blocking the turning process. Type C has space for one parked vehicle at one tail track. Note that the turning process changes to type B then. Additional parking spaces could be achieved by extending the platform tracks (type A) or the tail tracks (type B and C). To optimize flexibility, space usage and understandability for passengers, an island platform is chosen. These three terminal types are the basic ones: some combinations or alternative designs are of course also possible.

The analysis of these three types could also be used for assessing the effect of short turning infrastructure on the line. Short turning is a very widespread measure to restore service after major disturbances and in many rail networks, additional switches are constructed to enable short turning. Type A is similar to short turning with a double crossover before the platform, while in C the crossover is after the platform. Type B is similar to short turning infrastructure where only one crossover is available. This could be both from the right track to the left track or vice versa.

The infrastructure elements offer restrictions, regarding capacity. Hence, timetable and operational issues can be restrictive as well. The main factors affecting capacity are:

- Number of lines;
- Frequency;
- Coordination in case of more lines;
- Distribution of arrival times of vehicles;
- (Slack in) layover time.

In addition to these variables, the method of changing the driver is of great importance: is the driver changed at every turn (possibly saving the walking time from the front end to the rear end of the vehicle) or does he remain in his own vehicle, resulting in additional layover time (i.e. walking time)?

In this research, the time elements at the terminal are combined to "occupancy time". This time consists of the following elements (which are illustrated in figure 2) for type A:

- Approach time
  The time required to drive from entering the terminal at the switches to arrive at the platform. This time is a function of characteristics of the vehicles (acceleration, deceleration, maximum speed) and infrastructure (tail track length, maximum speed allowed at track and switches)
- Platform time
  The time between arrival at the platform and the time when the vehicle is ready to leave (according to the schedule and union agreements). Generally this time consists of:
    - Technical turning time
      The time to start up the vehicle to depart in the opposite direction (e.g. walking time of the driver to go the other part, start up the board computer)
    - Break
      The time the driver is allowed to rest (if not relieved)
    - Synchronization time
      The time needed to depart by schedule again. This time occurs if the cycle time is not an exact multiple of the headway.
    - Dwell time
      The time needed for passengers to alight or board
- Exit time
  The time required to drive from departing at the platform to leaving the terminal at the switches. This time is a function of characteristics of the vehicles (acceleration, deceleration, maximum speed) and infrastructure (tail track length, maximum speed allowed at track and switches).

For terminal type B and C the occupancy time consists of (illustrated in figure 2):

- Approach time
  The time required to drive from entering the terminal to arrive at the platform.
- Alighting time
  The time required for passenger to exit the vehicle after arrival at the terminal
- Tail track approach time
  The time required to drive from the platform to the tail track. This time is a function of characteristics of the vehicles (acceleration, deceleration, maximum speed) and infrastructure (tail track length, maximum speed allowed at track and switches)
- Tail track time
  The time between the arrival of the vehicle at the tail track and the time when it is ready to leave (according to the schedule and union agreements). Generally this time consists of:
    - Technical turning time
      The time to start up the vehicle to depart in the opposite direction (e.g. walking time of the driver to go the other section, start up the board computer)
    - Break
      The time the driver is allowed to rest
    - Synchronization time
      The time required to depart on schedule again. This time occurs if the cycle time is not an exact multiple of the headway.
- Tail track exit time

The time required to drive from departure at the tail track to arrive at the platform. This time is a function of characteristics of the vehicles (acceleration, deceleration, maximum speed) and infrastructure (tail track length, maximum speed allowed at track and switches).

- Boarding time
  The time required for passenger to enter the vehicle
- Exit time
  The time required to drive from departure at the platform to leaving the terminal.

It is important to note that in the case of no tail tracks certain time components, such as dwelling and technical turning, could occur at the same time, thereby saving total occupancy time. The break and synchronization time could be combined with boarding time in the case of one or two tail tracks. If signaling is applied the time mentioned above is extended by typical signaling time components, as switching time and clearance time. But this is not considered in this research.

4. TERMINALS AND THEIR IMPACT ON RELIABILITY

4.1 Calculation Model

A simulation tool has been developed to estimate the impact of the configuration of terminals shown in the previous paragraphs on service reliability and additional travel time for passengers. The tool generates arriving vehicles, considering both the schedule and deviations. Checks are made whether tracks are available. If not, waiting time is calculated until a track is available. At the platform track, turning is simulated as well as the departure of the vehicle. The output is the size and the probability of the delay per vehicle due to capacity restrictions. Without additional measures (e.g. slack in layover time), this delay will prevent vehicles from departing on time, leading to additional travel time for all passengers on the line. The previous paragraph already elaborated on this aspect. Further research could show the expected additional travel time for passengers due to the vehicle delay. This is yet not implemented in the model.

The simulation steps for all three types of terminals are shown by figure 3. Note that for type C three waiting queues are considered, while types A and B only have two possible queues. If no platform track is available, the vehicle has to wait in queue 1 (located at the access point). Queue 2 is located on the platform track and is used if a vehicle wants to depart while another one is entering (terminal type A) or when no tail track is available (terminal type B and C). If a vehicle is ready to depart the right tail track of terminal C and another vehicle just enters the left tail track, this vehicle has to wait as well (queue 3). To prevent waiting due to use of the double crossover by another vehicle, the preferred arrival track is the one where departing does not interfere with arriving.

4.2 Input and Output of the Model

The following input is used for the analysis. The model is run 30 times (one rush hour) with various combinations of these variables to calculate the average delay per vehicle.

- Service frequency: 4 to 24 vehicles per hour
- Occupancy time: 60-600 s. This time consists of:
  - Approach time
  - Technical turning time
  - Layover time
  - Egress time

  Chapter 3 described these elements in more detail
- The values for θ in equation 6 are (as proposed by (*3*)):

  θ_{stop} = 1.5

  θ_{RBT} = 0.7
- Arrival pattern: Arrival pattern of vehicles is modeled by using scheduled, even, headways and a distribution function of deviations, shown in figure 4.

The average delay per vehicle due to congestion at the terminal is the output of the model. This result is calculated by weighting the delays at the queuing locations (as described in the previous section) by the number of vehicles which have passed the specific queue.

4.3 Performance of Terminal Types

To assess the performance of terminals, the three key types are analyzed in a quantitative way, with respect to vehicle delays. The effect of various values for the main variables on the delay is assessed in order to develop graphs enabling quick scans during design. The average delay per vehicle is shown in figures 5, 6 and 7, respectively, for the three types of terminals. In these figures the occupancy time is one axis and on the other is the number of vehicles entering the terminal per hour. Arrival deviations as described in paragraph 4.2 are used as input. Besides, two values for the static occupancy are indicated as well (for every frequency analyzed): the green circles show the 50% static occupancy and the red circles show the 100% value (i.e. in theory, the terminal is utilized to the maximum extent).

The results of the terminal without tail tracks show that in the case of only a few vehicles per hour, delays arise almost in the case of 50% static occupancy. If frequency increases, delays start to occur when the static occupancy exceeds values of about 75%. For all frequencies analyzed, no delays occur if occupancy time is less than 240 s. If this value increases, the average delay increases quickly if the frequency is 20 vehicles or more per hour. Occupancy time of 420 s. creates significant delays for frequencies over 8 per hour.

If a terminal with one tail track is applied, the difference between the 50% and 100% of static occupancy is small (figure 6). Delays occur much sooner than in the case of the other two terminal types, due to the limited space for turning vehicles. No effects are to be expected if the occupancy time is less than 120 s. Frequencies equal or larger than 16 vehicles an hour show a large increase in delays if occupancy time exceeds this value. In general, delays arise if static occupancy reaches about 75%. Figure 6 also shows that if the frequency is 4 vehicles an hour or lower, no delays are to be expected at all.

The results of the two tail track terminal (figure 7) show that this type provides the best opportunities for dealing with larger numbers of vehicles. Below an occupancy time of 240 s. no delays are to be expected at all and for frequencies lower than 12 vehicles an hour, even 600 s. of occupancy time does not lead to significant delays. However, when the static occupation exceeds 90%, delays tend to increase quickly.

4.4 Impact of Arrival Pattern and Number of Lines on Delay

This section shows the effect of larger variability in arrival time deviations on the average delay. The frequency is set to 12 vehicles an hour. Figure 8 shows the used distribution of deviations of arrival time. This arrival pattern is heavier distributed than the one applied in the previous analyses. Actual data of a light rail line in The Hague, RandstadRail, is used (*6*). Figure 9 shows the results for all three terminal types. The average delay in the case of the regular schedule distribution is also shown.

Figure 9 illustrates that the effect of larger variability is negative: the average vehicle delay has increased in all cases. Compared to the regular distribution of deviations (figure 4) the average delay is about 20 s. longer. If the one and two tail track types are analyzed, delays start to arise with a lower value of occupancy time. The distribution of deviations is thus important to take into account when designing terminals. The majority of analyses consider only the schedule, which simply results in a static analysis.

The number of lines could also be of influence on performance. For the total frequency of 12 vehicles an hour, an analysis is made of both one line and two lines. Both lines have the same schedule deviation distribution (figure 4) and they are not optimally coordinated (no evenly scheduled headways). Note that if they are optimally coordinated there is no difference between one or two lines (if both lines have similar schedule adherence). The difference between the scheduled arrivals of both lines (off-set) is set to 3 min. (and 7 min.). Figure 10 shows the results.

Figure 10 clearly indicates that the effect of two lines is negative, compared to one line offering the same total frequency. Besides the increase in delays, the occupation time, when delays are getting introduced decreases as well. These results show that while assessing terminals' capacity, the number of lines and their (lack of) coordination is important.

5. CONCLUSIONS

Reliability is one of the key quality characteristics in urban public transport. Unreliability of the public transport system extends travel time and thereby competition with other modes will be harder. This paper deals with the impact of rail terminals on reliability. Although reliability is considered to be very important, less attention is paid to preventing deviations by designing optimal terminals and short turn facilities. During the (infrastructure) design process of public transport, reliability is not explicitly taken into account, which could lead to suboptimal terminals. Although, operational and/or timetable measures can heal the effects of the suboptimal design, this is just partially.

In this paper, it is suggested to consider reliability already during infrastructure design and the mechanisms and effects of infrastructure design are shown. Calculations of the average delay per vehicle, regarding three main types of terminals, show the effect of frequency on the one hand and occupancy time (determined by the distance from the switches to the platform, technical turning time and scheduled layover time) on the other. The substantial effect of arrival variability and the number of lines using the terminal is illustrated as well. It is shown that using stochastic variables, delays will occur, although they are not to be expected in the static case. The best performance regarding reliability is achieved, when double crossovers are situated after the platforms. Single tailtracks facilitating the turning process are only acceptable if frequencies are low. Although, , they are often used in practice as short tuning facility for high frequent services. This research shows the large impact of occupancy time on expected delays. It is recommended to minimize this time by designing short distances between switches and platform and tailtracks.

Capacity management is not common use in transit. However, increasing frequencies and large deviations force to consider limited capacity, while planning infrastructure. If not, delays will occur and additional measures are necessary to solve them. This could be more expensive in the long run.

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TABLE 1 Characteristics Case Lines

Line	Direction	Headway [mins.]	Length [km]
1	Delft (DT)	10	20
2	Leidschendam (LD)	8	13
9	Scheveningen (SN)	5	14
11	Station Hollands Spoor (HS)	10	8
12	Station Hollands Spoor (HS)	8	7
15	Moerwijk (MW)	8	17
17	Statenkwartier (ST)	8	16

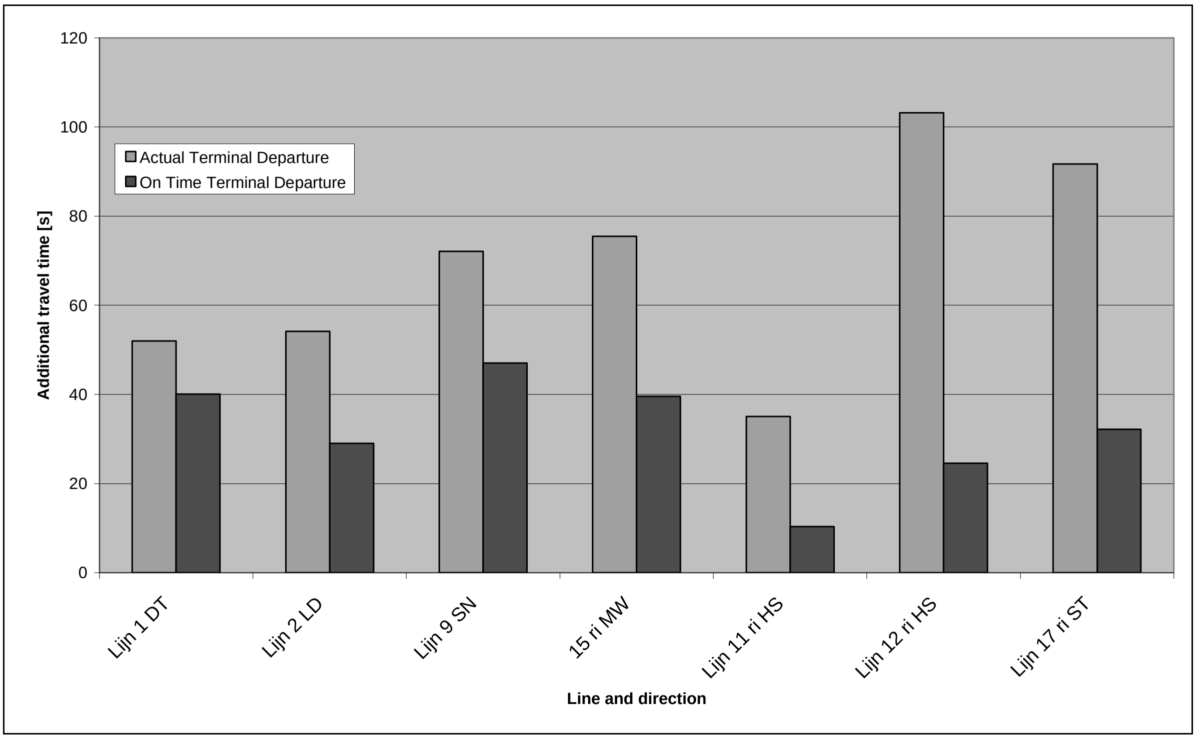
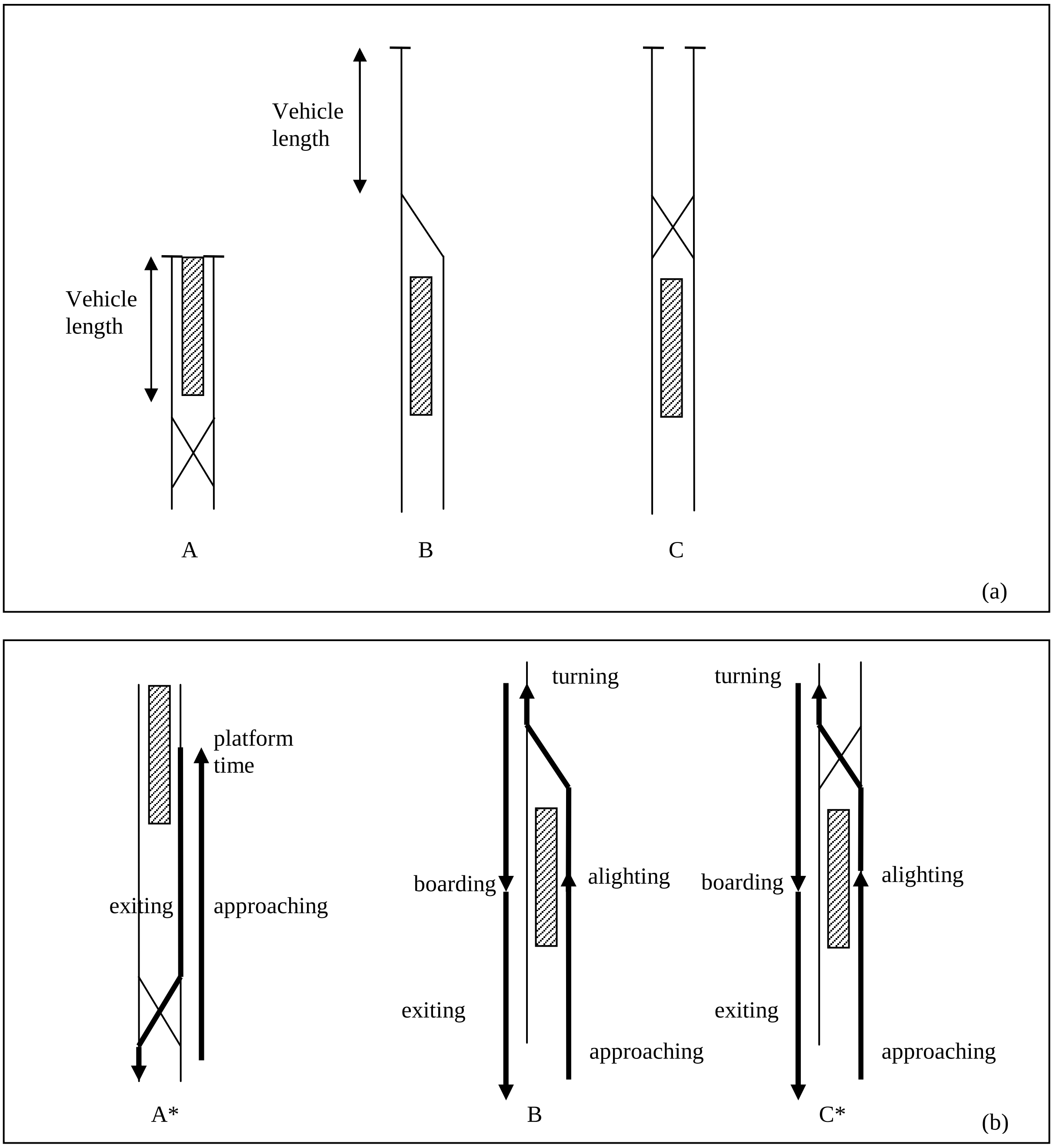


FIGURE 1 Effect of on Time Departure at Terminal on Additional Travel Time per Passenger.



** The other tail track could be used for turning as well*

FIGURE 2 Three commonly used Terminal Types (a) and Processes (b).

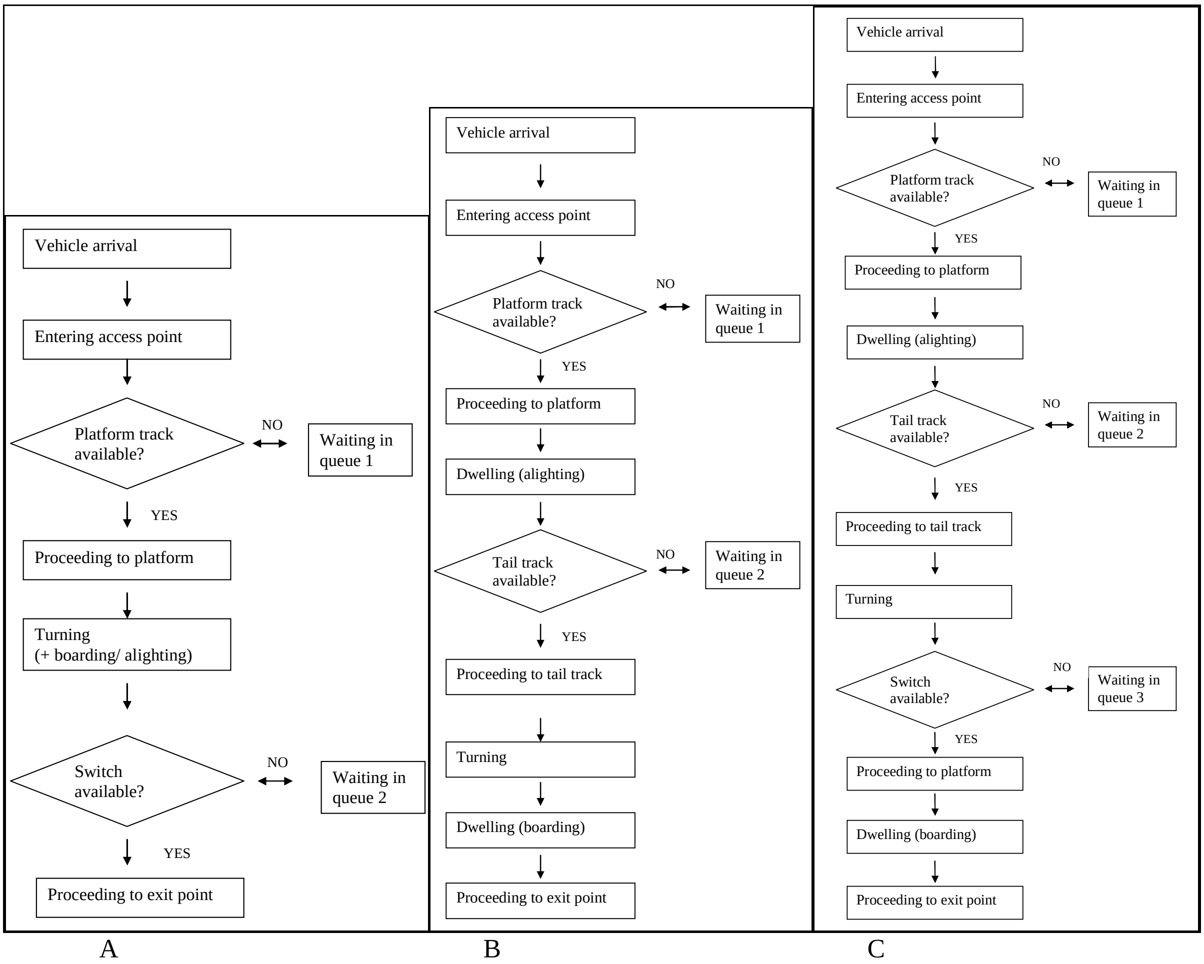


FIGURE 3 Simulation Steps for Three Terminal Types (A= No Tail Tracks, B= 1 Tail Track and C= 2 Tail Tracks).

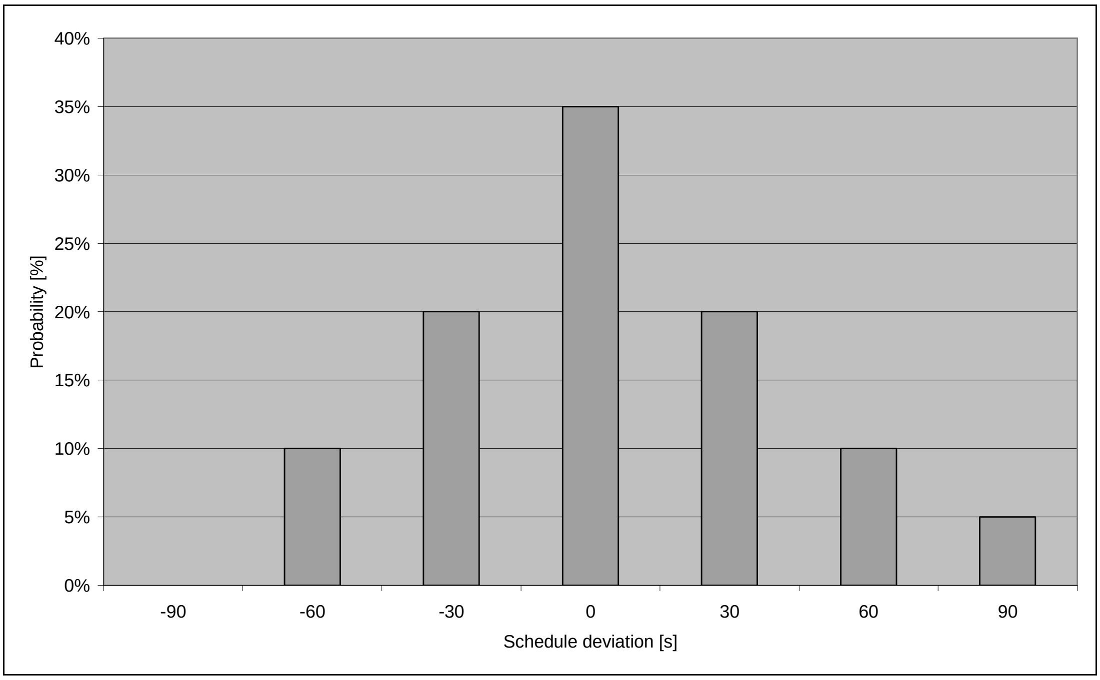


FIGURE 4 Variability in Arrival Time Deviations.

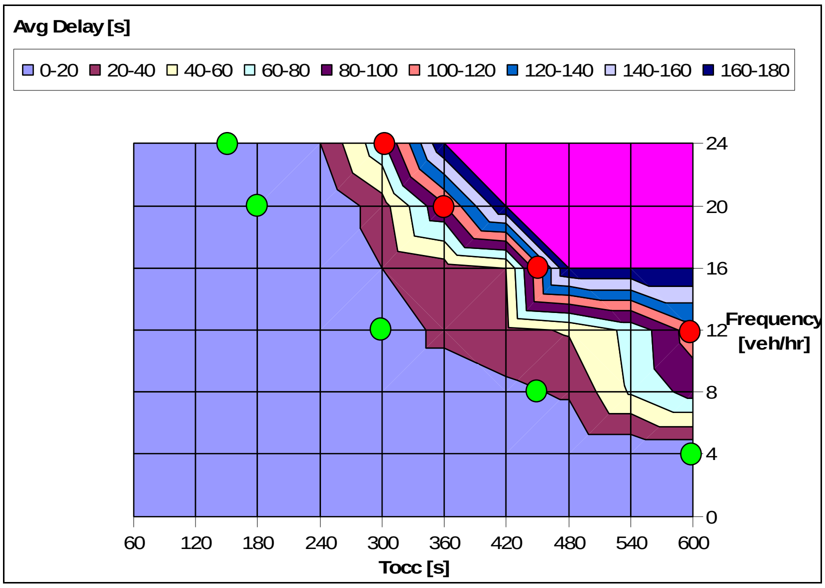


FIGURE 5 Average Delay as a Function of Occupancy Time and Service Frequency, no Tail Tracks.

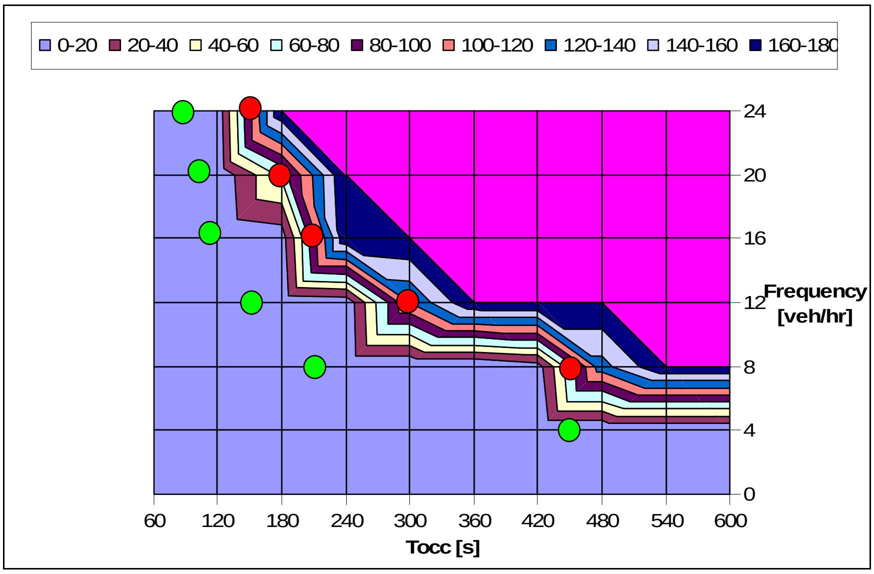


FIGURE 6 Average Delay as a Function of Occupancy Time and Service Frequency, one Tail Track.

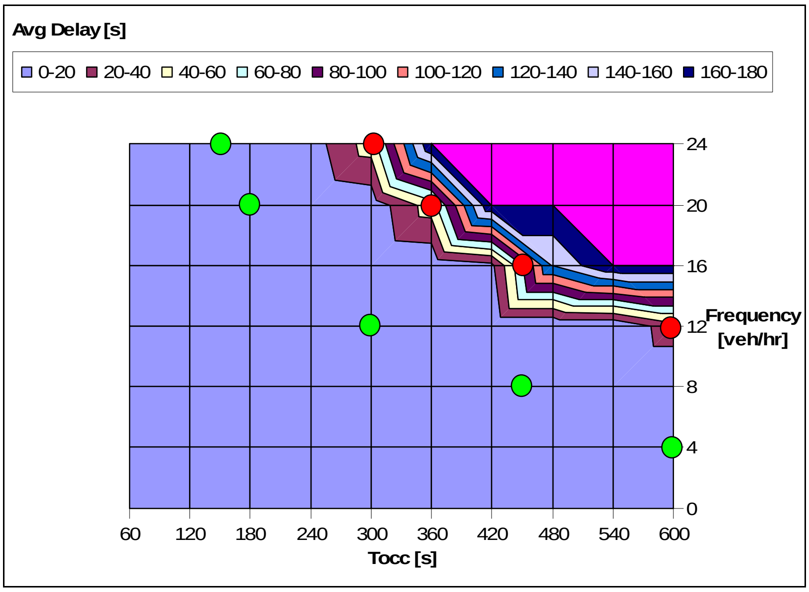


FIGURE 7 Average Delay as a Function of Occupancy Time and Service Frequency, two Tail Tracks.

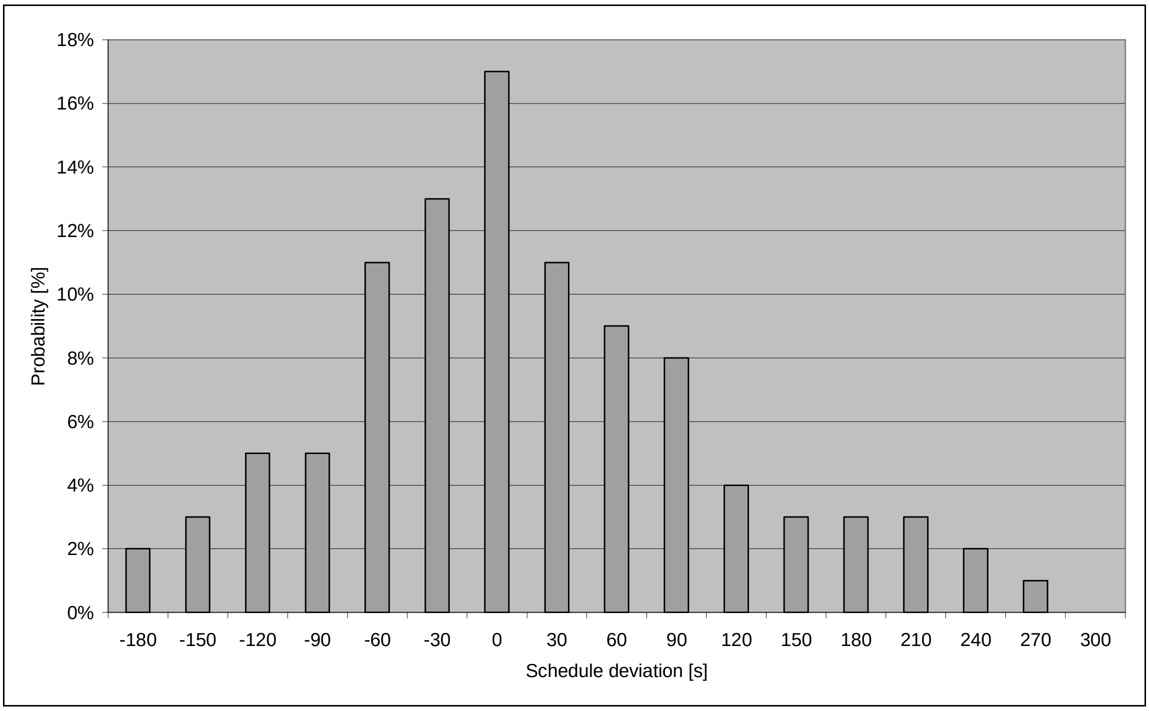


FIGURE 8 Distribution of Schedule Deviations, heavily disturbed Case.

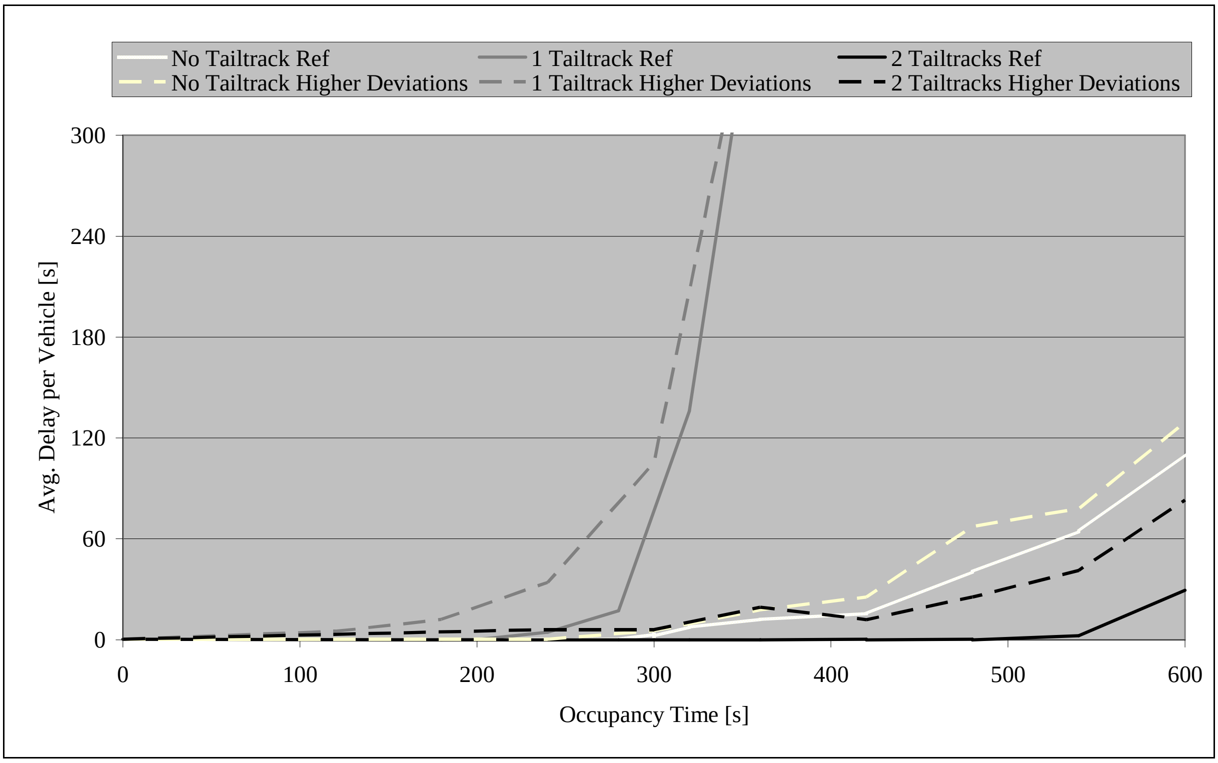


FIGURE 9 Effects of Schedule Deviations on Average Delay per Vehicle at Terminals.

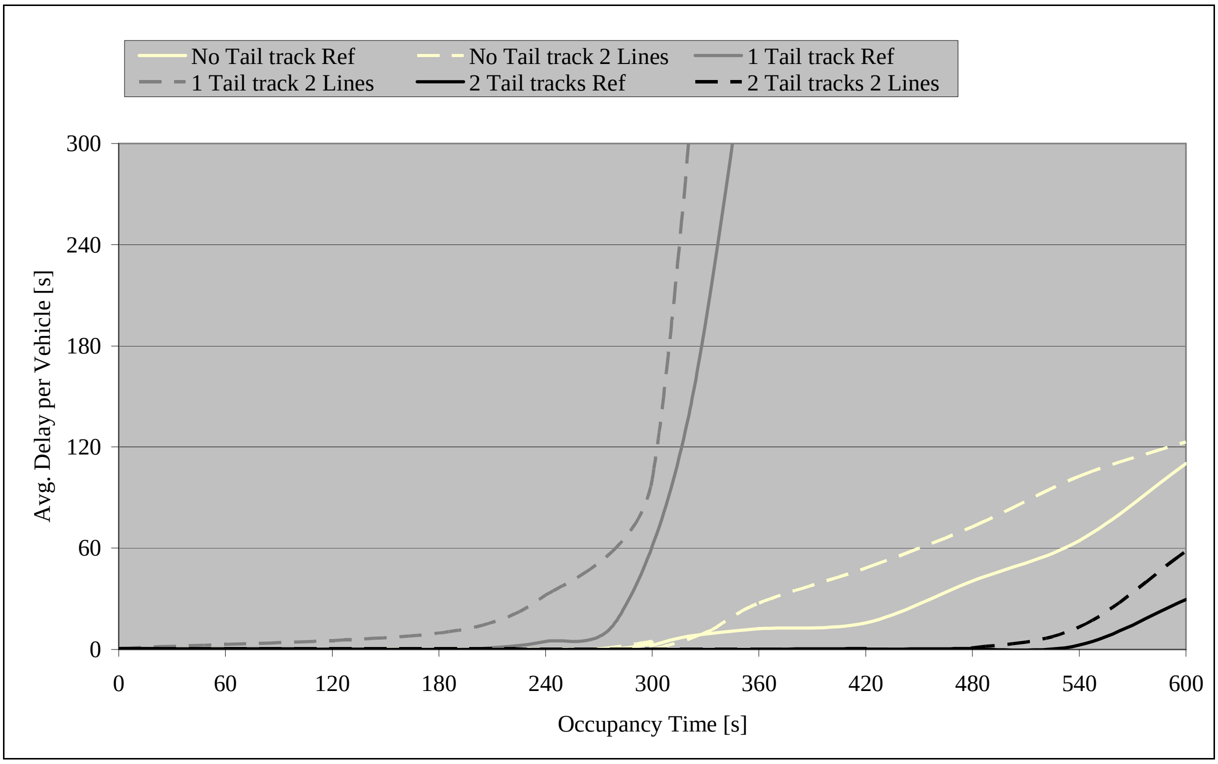


FIGURE 10 Effects of Number of Lines at Terminals on Average Delay per Vehicle, Total Frequency of 12 veh/hour.