Analysis of The Uithof Tram Line

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1 Introduction

The Uithof in Utrecht houses the majority of faculty and facilities of Utrecht University. Because of its location near the edge of the city, commuting students and staff have to travel through the busy city centre daily. To relieve traffic, Qbuzz (Utrecht public transport) will replace the current bus system by a tram line in early 2019. The route and the amount of stops will differ slightly from that of the bus. However, since trams fit more people and have different properties (e.g. top speed) than busses, the current driving schedule is not well suited. Therefore, a new schedule has to be fitted. This report focuses on implementing a discrete-event simulation of the new Uithof line, constructing a new timetable, and computing the capabilities of the new tram system.

A timetable is designed based upon the quality measures of *punctuality* and *passenger waiting times*. The simulated percentage of trams with a delay of over one minute, as well as maximum and average delays determine the punctuality of the schedule. The passenger waiting time measures cover the maximum and average waiting times of commuters before boarding as well as the percentage of passengers never to board a tram (e.g. having queued so long that the last tram already left). In order to find a qualitative schedule for the tram, these measures need to be optimised together. Moreover, the lines capabilities are computed as the maximum amount of daily passengers the line can handle.

Summing up, the main questions answered in this report are to determine what a feasible schedule for the Uithof line is, and what the capabilities of the tram line are. In order to answer these questions, the Uithof line is simulated for different schedules. In the next subsection we describe the layout of the tram line, and the restrictions for the schedule. Based on those requirements and the presented quality measures, a schedule is designed and discussed.

2 Layout of the Uithof line

2.1 Assumptions & requirements

In order to design a timetable and compute capabilities, the requirements and restrictions of the Uithof line need to be known. Here we present a brief overview of the workings of the trams, the restrictions for the schedule and the structure of the line itself.

Trams running on the Uithof line always run in doubles, which means two carriages are linked together. They share a capacity of 420 passengers. There is no restriction on the number trams that can run simultaneously. Furthermore, there exists a minimum driving time between stops, as trams do not run faster than 70km/hour[1]. We assume that trams need 5 seconds to get to maximum speed or to a full halt. This makes the minimum driving time between stops in minutes $t_{min} = \frac{60 \cdot (d-0,097)}{70} + \frac{1}{6}$, where d is the distance in kilometres between stops.

Another assumption concerning the tram and time, is that it takes a tram 40 seconds to emerge at the platform, when queued behind another tram. That is, if a platform is occupied when a tram arrives, it will take 40 seconds for the tram to arrive at the platform once it is available. The time spent on the platform unloading and accepting new passengers is called the *dwell time*. This dwell time depends on the amount of commuters going on and off and can be described by a gamma distribution where shape $k = 2$ and $mean = 0.8 \cdot d$, with $d = 12.5 + 0.22 \cdot passengers_{on} + 0.13 \cdot passengers_{off}$.

Because of the location and function of the Uithof, commuters are expected to arrive at stops in larger quantities during rush hours. Thus, different frequencies of tram departures are required during the day. In this simulation we assume three different frequencies: during rush hours, during the day, and during off-peak hours. Note that trams are scheduled to run from 6:00 to 22:00, as this is mainly a commuter line. From 6:00 to 7:00 and from 18:00 to 21:00 an off-peak rate is proposed. In rush hours, from 7:00 to 9:00 and 16:00 to 18:00, the trams depart with a higher frequency. Last, a day rate is established from 9:00 to 16:00. The optimal frequencies determine the schedule of the tram line.

On the structure of the line itself: The Uithof line consists of nine stops (table 1). As the marshalling yard is located at Uithof P+R, all new trams may only depart here. To simplify this requirement, we do not take the time it takes for a tram to drive from the marshalling yard to the platform into account. Trams continue heading to Utrecht central station, and then head back. The schematic layout of the track can be seen from Figure 1. Note that normal stops only have one platform for each direction, while the two end stations have two platforms that can station two trams simultaneously. Trams have to cross a switch on either its way in or out of the end station, i.e. before or after it reaches the platform. Whenever there is a tram using the switch, no other trams can pass for one minute as a safety measure for collisions. However, two trams that operate the two opposing straight tracks instead of the crossing, clearly may leave and arrive at the end station at the same time.

[1]See the interview with Qbuzz in the appendix.

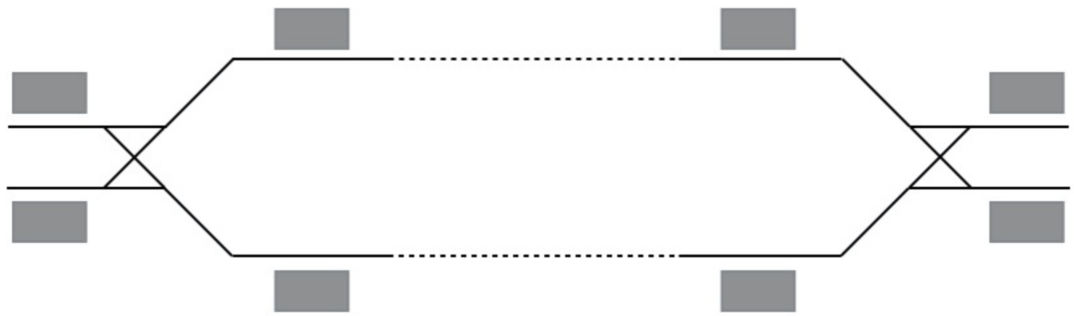


Figure 1: Schematic layout of the track, with platforms represented as grey blocks.

Bus stop	Tram stop
	Uithof P+R
	WKZ
AZU	UMC
Heidelberglaan	Heidelberglaan
Padualaan	Padualaan
Kromme Rijn	Kromme Rijn
Galgenwaard	Galgenwaard
Bleekstraat	Vaartsche Rijn
Centraal Station	Centraal Station

Table 1: Stops of the new tram line and their corresponding stops of the old bus line.

While serving passengers at one of the end stations, trams also have to change direction. This procedure takes at least three minutes, as the driver has to set up the back of the tram as the new front. During this time passengers can board and exit the tram. So, instead of sampling the dwell time from the gamma distribution, the end stations have a set waiting time called *turn around time* q. In our simulations of the Uithof line, the efficiency and capacity of the line will be measured using different values of q.

2.2 Analysis of the problem

The Uithof line needs to be simulated in order to answer the research questions. However, we can base some expectations on data provided by public transport company Qbuzz. Firstly, the company offers a passenger prognosis for every stop of the tram line, including separate prognosis for rush hours. From this prognosis we can estimate feasible frequencies for the tram schedule. The total commuters expected is 45,000 during the full day, and 10,283 and 10,553 during morning and evening rush hours respectively. Central station is the busiest stop in the morning, with 8123 commuters trying to get on the tram during rush hour. Thus, one tram capacity of passengers is expected to arrive there every 6.2 minutes. During the evening rush hour the stops surrounding the university buildings (Padualaan and Heidelberg) are the busiest and expect 5766 arriving passengers, i.e. one tram capacity every 8.7

minutes. However, arriving passengers at other stops need to be accounted for too. As an maximum of 9285 commuters arrive during rush hour over all stops on the busiest route, a full load of 420 passengers arrives across stops every 5.4 minutes. Therefore we expect a rush hour rate of 11 trams per hour to be a feasible rate.

During the rest of the day, both central station and the stops surrounding the campus are equally busy with arriving passengers. In total an average of 12,082 commuters arrive in 12.5 hours, that makes one tram load across all stops every 26 minutes. A rate of 3 trams per hour is therefore expected to be feasible during the day. Still, off-peak rates may turn out to differ from the mid day rate, as classes at the university start and end during all working hours.

Secondly, the expected schedule of 11 trams per hour during rush hours and 3 trams per hour for the rest of the day, determines the total amount of passengers the line can handle. Multiplying the amount of rides throughout the day with the maximum amount of passengers that fit inside a tram, we find $2 * 420 * (11 * 4 + 3 * 12.5) = 68,460$ commuters. With this, the capacity of the tram line exceeds the prognosis by 23,460 passengers.

3 Model

In this section we explain the model we use for the simulation of the Uithof line. The structure of the model (servers and queues) is explained first, followed by the different types of events used in the discrete time simulation. Last, we expand on the performance measures used to test the model.

In order to perform a correct and efficient simulation of the Uithof line, we need to implement a structure where trams arrive and depart at tramstops without overtaking one another. That is, we need to implement a queuing process where trams as well as passengers form First-in-First-Out (FIFO) queues at tramstops. In this scenario, tramstops act as servers that are either idle or occupied, i.e. whether or not a tram is currently stationed at the tramstop. See Figure 2 of a schematic overview. As trams that are headed for the Uithof operate different tracks than trams headed for Utrecht Central Station, trams queue in two separate queues depending on their direction. Clearly, the same holds for passengers as they are headed for either of the two directions. As as result, tramstops can be split in two, one for trams and passengers that are headed for the Uithof and one for trams and passengers that are headed for Central Station. As a result, trams run in circuits that start and finish at the Uithof, as can be seen from Figure 1.

The same does not hold for end stations, as they contain a single tram queue, a FIFO passenger queue, and two platforms where trams can be stationed. Trams heading into the end station queue at the switch if the switch is occupied or if no platform is available. They then continue to their assigned platform and will possibly queue again on their way out of the station if the switch is occupied. Hence, we schedule three arrivals and departures within one end station: two at the switch and one at the platform. Some of these arrivals and departures can be instant and will not delay the tram, e.g. if the switch is idle and the tram is departing the platform. However, as there might be delays at each point, individual arrivals and departures need to be scheduled.

The two main types of events are *tram arrives at stop* and *tram departs from stop*. These are the events that regulate the time in the simulation. That is, all generated events are placed in a priority queue and the time at which the next event occurs, is the next time state of the simulation. The events are generated as trams traverse the Uithof line: when a tram arrives at a stop, its departure event is scheduled, and whenever a tram departs, the arrival at the next stop is generated. One exception to this is at the Uithof P+R, where the timetable determines whether the tram is rescheduled to a departure again or if it returns to the marshalling yard.

Passenger arrivals also need to be generated during the simulation. As a large number of passengers are expected to arrive throughout the day, passenger arrivals are not generated as events. However,

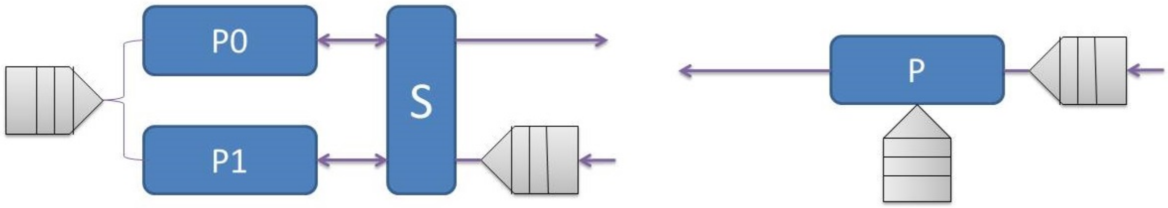


Figure 2: Schematic layout of end stations (left) and trams tops (right). *Left*: Trams queue at the switch (S), then continue to platform P0 or P1, where passengers are queued to board the tram. Upon leaving the platform, trams may queue at the switch if it is occupied. *Right*: Trams and passengers queue at the platform.

they are generated locally to a tram stop during each tram arrival. The interval that is used for passenger generation covers the departure time of the previous tram till the departure time of the current tram. To accurately estimate the maximum waiting time, interarrival times are estimated by exponential distributions corresponding to the expected number of arrivals for the current tram stop and time. Passenger arrivals are generated and queued until the interval is exceeded.

As we expect as many passenger departures as arrivals, passenger departures are also generated locally to each tram stop with each tram arrival. As the number of departing passengers depends on the number of passengers in the tram, it is estimated by a binomial distribution with a p-value corresponding to the probability a passenger exits. This probability is determined by the total number of expected exiting passengers for the current tram stop and time.

We discuss how the parameters of each distributions were determined in the next section. The parameters of the passenger distributions fluctuate throughout the day. For instance, morning rush hour brings students and staff to campus, while evening rush hour brings them back. Hence, the passenger parameters are determined for each tram stop every 15 minutes. This makes for 64 ($= 16h/15min$) different states of the parameters.

In order to account for the rush hour streams (towards the campus in the morning, and back to the train station in the afternoon) and the fact that trams start their round at the Uithof, we let the morning rush hour start 17 minutes early. Now the first rush hour trams arrive at central station when the true rush hour starts.

Lastly, we discuss the performance measures, which have already been briefly introduced. The percentage of trams that leave one of the end stations with a delay of over one minute and the maximum and average departure delays, contribute to the *punctuality* of the timetable. These three values are calculated at both end stations and should be minimised by the schedule. The maximum and average passenger waiting time in a queue contribute to the *passenger waiting times*. Furthermore, as trams departures at the Uithof P+R are only allowed till 21:40, the amount of commuters left at tram stops at the end of a simulation is also a performance measure for passenger waiting times. Namely, if this amount is large, it indicates full trams or heavy delays at the end of the day. Thus, we want the three values of the *passengers waiting times* measure to be minimised by the schedule as well.

4 Input analysis

4.1 Run times

Distributions of the run time between tram stops was estimated using run time data from tram line 60, which runs between Utrecht Central Station and Nieuwegein and is operated by the same high-speed trams that will be employed at the Uithof line[2]. The data set contains run time measurements from 1259 tram runs between 14 different stops. The distance between each two consecutive trams tops of line 60 was traced in Google Maps to compute average speed and acceleration. Allowing for at least 5 seconds to gain maximum speed or to reach full halt, all entries which implied an average speed of over 70km/h, i.e. for which the run time was smaller than t_{min}, were marked as erroneous. As a result, 207 tram runs (16% of all runs) that contained false entries were removed from the input data.

The distributions of the run times between each two consecutive tram stops in the resulting data set was analysed using RStudio version 1.1.425. Histograms of each distribution implied that they resembled normal distributions with a slight positive skew. Previous research in travel and dwell times suggests using a log normal distribution, or other positively skewed distributions (Buechel and Corman, 2018).Therefore, each distribution was fitted to a normal, log-normal and gamma distribution using the fitdistrplus package[3]. The goodness-of-fit of each fitted distribution was visually examined using Q-Q plots, see Figure 3. All fitted distributions performed similar, but contained less low-valued and more high-valued observations than could be expected from the three distributions. The lack of low-valued observations is a direct result of allowing only run times above t_{min} in our data set, while the excess of high-valued observations might be a result of unforeseen circumstances, such as traffic accidents.

As the total Akaike's Information Criterion score over all tram stops for the log-normal distribution (104152.1) was slightly lower than the gamma distribution (105363.6) and considerably lower than the normal distribution (108441.5), it fitted the data best. Hence, the run times between stops at the Uithof line are simulated as log-normal distributions.

While our data contained the average distance and driving time between each two stops from the Uithof line, the variance of the log-normal distributions had to be estimated from our line 60 run time data set. As the run time variance is linked to distance as well as average speed, a negative correlation was found between run time variance and average acceleration between stops. That is, if a tram is not able to accelerate on a track, for instance as a result of busy traffic, the run time variance will be high. We estimated the variance between each two stops as a function of average acceleration by fitting polynomial, exponential and power functions. We compared the goodness-of-fit of these models using the Pearson's χ^2 test statistic. The fitted exponential function $\hat{var}_{EXP}(a) = 1550.9e^{0.002a}$ with $\chi^2 = 3198.7$ scored the worst fit-score while the power function $\hat{var}_{POW}(s) = 5 \cdot 10^{11} \cdot a^{-3.067}$ with $\chi^2 = 2144.192$ scored slightly better and the polynomial function $\hat{var}_{POL}(a) = 0.0002a^2 - 0.843 + 1020.70$ with $\chi^2 = 1635.33$ scored best. Therefore, the polynomial function $\hat{var}_{POL}(a)$ was used to estimate our run time variance as a function of average acceleration between stops. See Table 2 for the fitted model and resulting run time variances.

4.2 Passenger arrival and departure

Our data contained passenger arrival and exit rates for each stop of the current bus line to the Uithof. These rates date from 2015 and cover 21 days of measured data with an average of 304 single runs a day, i.e. from the Uithof to Central Station or back. As the tram stop Vaartsche Rijn will be replacing

[2]This data is made available by QBuzz.
[3]https://cran.r-project.org/web/packages/fitdistrplus/fitdistrplus.pdf

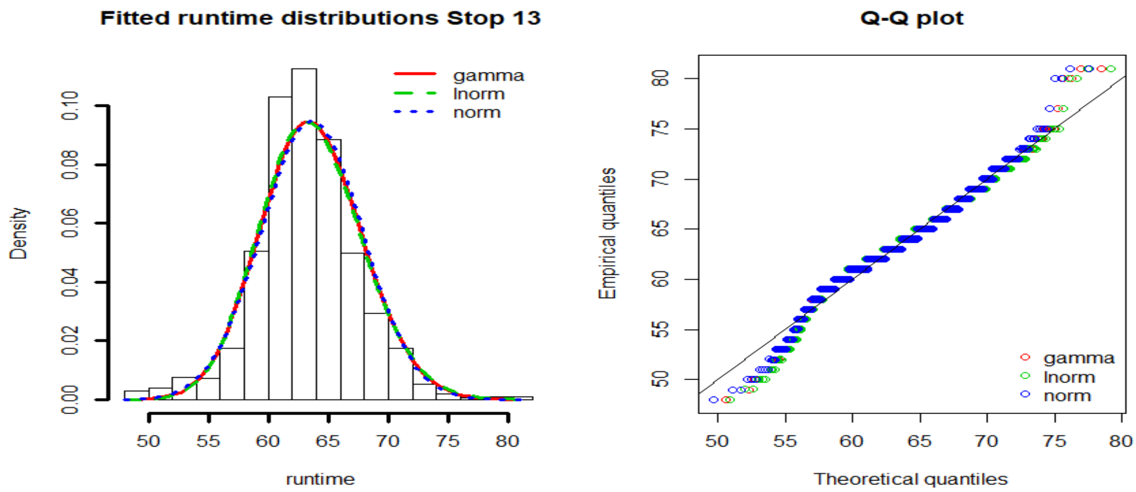
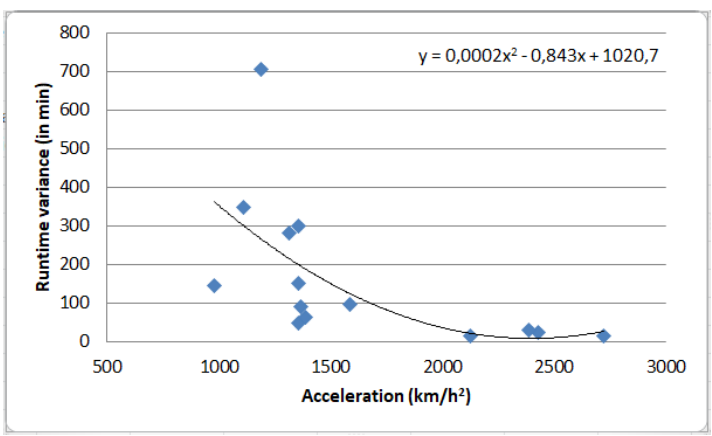


Figure 3: Goodness-of-fit using fitted normal, log-normal and gamma distributions to run times of tram stop *Wiersdijk*.



Stop	μ	$v\hat{a}r_{POL}(a)$
WKZ	110	561.55
AZU	78	269.97
Heidelberglaan	82	489.65
Padualaan	60	221.5
De Kromme Rijn	100	361.67
Galgenwaard	59	135.58
Vaarts. Rijn	243	539.72
CS	135	379.67
Vaarts. Rijn	134	373.08
Galgenwaard	243	539.72
De Kromme Rijn	59	135.58
Padualaan	101	370.50
Heidelberglaan	60	221.5
AZU	86	528.08
WKZ	78	269.96
Uithof	113	581.50

Table 2: Estimating run time variance as a function of average acceleration. *Left*: fit of $v\hat{a}r_{POL}(a)$ to run time variance between each stop of tram line 60. *Right:* estimated run time mean μ and variance $v\hat{a}r_{POL}(a)$ in seconds of between Uithof line stops.

bus stops Bleekstraat, Sterrenwijk and Rubenslaan, passenger arrival and exit rates were summed, hence assuming passengers heading to and from these stops will be using the tram line in the future.

Each arrival entry for each stop was assigned one of the 64 time slots, after adjusting for added run time between stops. That is, for each stop we add the average run time and a mean dwell time of 19 seconds to the expected departure from the previous stop to gain its adjusted time slot. For instance, if a bus departs at AZU at 6:11 the number of exiting passengers at Central station will belong to time slot 1 as its expected arrival time is 6:28. The mean dwell time is calculated by dividing the difference of the total run time and the expected 17 min it takes for a single trip, by the total number of stops made.

As the number of passengers to the Uithof has been increasing, the total number of passengers per time block (morning/evening rush hour and day total) is scaled linearly to its 2020 prognosis. The same is done for the exiting probabilities as these do not equal the 2015 rates. In case of missing information, e.g. no bus departed from Central Station in time slot 1, rates are estimated by taking mean of next and previous time slot. One outlier was removed during this process, which contained measurements taken on the 2nd of September, which is the first day of the academic school year, at 6:11 which shows 18 times as many passengers arrivals than usual.

5 Output Analysis

In this section, we analyse the performance of our model. First, we will determine a feasible schedule using three performance measures: maximum passenger waiting time, average tram delays at end stations and the number of passengers not able to reach their destination. We will use the best performing schedule to further analyse the performance of our model. Lastly, we validate how our input parameters fit our expected results.

5.1 Determining a feasible schedule

To determine a feasible schedule, different departure rates and values of q were tested. The turn-around time q was tested between 3 and 5 minutes, while rush hour rates were tested between 10 and 15 trams per hour, and day and off-peak rates between 4 and 8. Each set of parameters was tested 10 times.

Maximum passenger waiting times were minimised by high tram rates and high values of q, as more tram departures clearly imply less time waiting for a tram to arrive. The top 10 schedules that minimised the maximum waiting time were tested with two-sided t-tests against other schedules and showed significantly higher rush hour rates ($p=7.84 \cdot 10^{-5}$), day rates ($p=0.035$) and off-peak rates ($p=0.039$). No significant results were found for the turn-around time q.

The maximum waiting time of the top performing schedule equalled only 18.44 minutes over the entire day while some passengers had to wait 99.66 minutes in the worst performing schedule. The maximum waiting time of the top 10 performing schedules equalled 19.08 with an average q of 4.3 minutes, a rush hour rate of 13.9 trams/hour and day and off-peak rates of 6.2 and 6.0 trams/hour.

Average tram delays at end stations were minimised by lower tram rates and low values of q, as clearly less trams imply less queues and therefore less tram delays. Using two-sided t-tests, the top 10 ranking schedules that best minimised the average tram delay showed significantly lower q ($p=8.83 \cdot 10^{-4}$) and rush hour rates ($p=6.86 \cdot 10^{-6}$). No significant results were found for day and off-peak rates.

The average tram delay of the top performing schedule equalled 4.838 minutes while trams were delayed for an average of 51.526 minutes in the worst performing schedule. The average delay of the top 10 performing schedules equalled 5.289 minutes with an average q of 3.3 minutes, a rush hour rate of 10.4 trams/hour and day and off-peak rates of 5.7 and 5.2 trams/hour respectively.

All passengers were able to reach their destination in 99.5% of the simulations. In the remaining simulations, between 1 and 1063 passengers were unable to reach their destination. Two-sided t-test showed these worst-performing schedules had significantly lower q (p=0.049), rush hour rates (p=$5.69 \cdot 10^{-14}$) and off-peak rates (p=$1.21 \cdot 10^{-55}$). Day rates were significantly higher (p=$4.56 \cdot 10^{-20}$).

The overall top performing schedule was required to minimise both the maximum waiting time, the average tram delay and the number of passengers that were not able to reach their destination. Hence, the schedules with the lowest summed rank for all three quality measures was determined as the top overall-performers. The top 10 overall-performing schedules showed significantly lower q values (p=$8.83 \cdot 10^{-4}$), as could be expected from minimising the tram delays, and significantly higher day rates (p=0.036) as could be expected from minimising the maximum waiting time. No significant results were found for rush hour rates, as the effects of minimising over both maximum waiting time and tram delays evened each other out.

In the next section we analyse the performance of our simulation using the top overall-performing schedule, i.e. the schedule with a q of 4 minutes, a rush hour rate of 12 trams/hour and day and off-peak rates of 6 trams/hour. The simulation was performed 100 times in order to statistically analyse the performance measures: maximum and average tram delays at end stations, fraction of trams delayed, maximum and average waiting times and the number of passengers unable to reach their destination.

5.2 Performance of the model

With the top performing schedule the capabilities of the tram line are as follows: the maximum amount of passengers that can be transported by the trams is $2 \cdot 420 \cdot (12 \cdot 4 + 6 \cdot 7 + 6 \cdot 5.5) = 103320$. In this case, every tram running the track will always be full. The capacity exceeds the prognosis by 58,320 passengers.

The maximum and average tram delays at end stations equalled on average (+-standard variation) 31.35 (+-6.40) minutes and 7.87 (+-2.32) minutes respectively. Following a two-sided t-test, these results were significantly higher than the maximum (p=$8.66 \cdot 10^{-11}$) and average (p=$2.81 \cdot 10^{-24}$) delay at regular tram stops. Maximum delays were 95 percent likely to be between 1.42 and 5.19 minutes higher at end stations than regular tram stops, while average delays were likely to be between 1.29 and 2.72 minutes higher. This increase in tram delays is most likely a result of high dwell times (i.e. 4 minutes) at end stations compared to regular tram stops.

Maximum and average tram delays were significantly higher at Uithof P+R than at Central station (p=$4.28 \cdot 10^{-20}$ and p=$1.89 \cdot 10^{-52}$ respectively). The maximum delay at Uithof P+R was 95 percent likely between 3.31 and 6.36 minutes higher than the maximum delay at Central station, where average delays were 95 percent likely to be between 2.56 and 3.30 minutes higher. This is most likely a result rescheduled trams occupying all platforms at Uithof P+R. As trams depart at least every 6 minutes, a tram might occupy a platform at Uithof P+R for 6 minutes, while this is only 4 minutes for Central Station. Hence, this causes more tram delays at the Uithof.

Tram delays accumulate over the course of the trams round trip, as can be seen from Figure 4. Clearly, the probability that the tram queues behind delayed trams accumulates as it traverses the track. For example, the maximum and average delays at the last regular trams top (WKZ) were significantly higher (p=$6.44 \cdot 10^{-27}$ and p=$9.7 \cdot 10^{-62}$ respectively) than the first tram stop (WKZ). The maximum delay of the last stop were 95 percent likely to be between 8.83 and 12.20 minutes higher than the first stop. On average, the delay was between 5.89 and 6.80 minutes higher at end stops than at the first stop.

The time at which maximum delays at ends stations were reached was 95 percent likely to be between 14:41 and 16:09. As no new trams are scheduled from the morning rush hour until evening

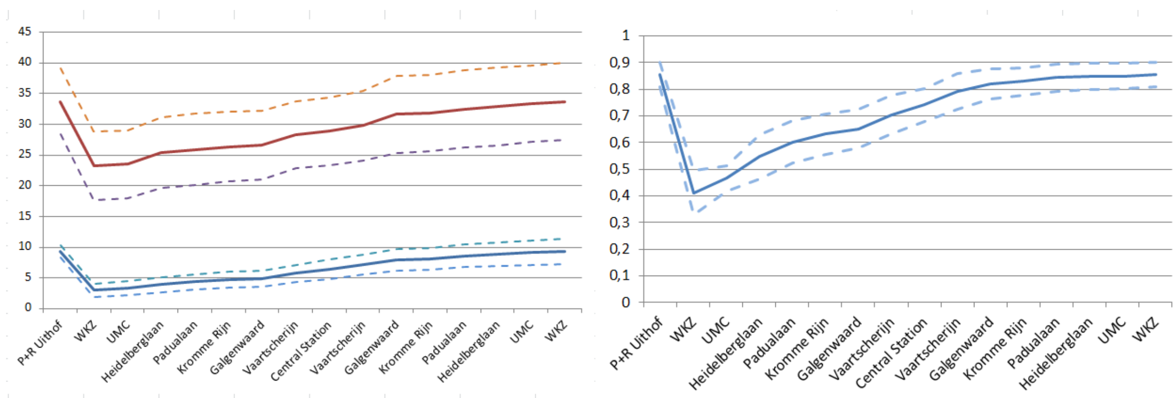


Figure 4: *Left:* Maximum (red) and average (blue) delays per trams top. *Right:* Average fraction of delayed trams per tram stop. Dotted lines represent the standard deviation observed over 100 simulations.

rush hour, it is likely that these delays were accumulated over the course of the day. For instance, if a tram arrives at at Uithof P+R with a 8 minute delay during rush hour, it will be scheduled with a 4 minute delay, as we scheduled in 4 minutes of 'buffer' time.

The maximum and average waiting passenger time equalled on average (+-standard variation) 22.28 (+- 12.58) minutes and 6.60 (+-2.57) minutes respectively. The maximum waiting time at end stations was significantly lower ($p=1.47 \cdot 10^{-15}$) than at regular tram stops, while no such significant results were found for the average waiting time at end stations. The maximum waiting time at end station was 95 percent likely to be between 6.395 and 6.398 minutes lower than at regular tram stops. The maximum waiting time is likely to be lower for end stations as all passengers exit at end stations and the full capacity of trams are available, i.e. 420 passengers may board.

Maximum and average passenger waiting time was significantly higher at tram stop Vaartsche Rijn than at other tram stops ($p=5.41 \cdot 10^{-32}$ and $p=4.68 \cdot 10^{-31}$ respectively). Maximum waiting passenger times at Vaartsche Rijn were 95 percent likely to be between 22.42 and 29.41 minutes higher than at other tram stops, and average waiting times between 6.30 and 8.10 minutes, see Figure 5. The time at which the maximum waiting time was reached at Vaartsche Rijn was on average around 9:13 (+-1:49) and significantly lower than at the rest of the tram stops, which reached their maximum waiting time around 14:45 (+-4:18) ($p=3.24 \cdot 10^{-63}$). This implies that passengers at Vaartsche Rijn are not able to board in the morning rush, most likely to trams having reached their full capacity at Central Station.

All passengers were able to reach their destination in all 100 simulations.

5.3 Validation of Input Parameters

In order to validate our simulation, all models and their input parameters need to be validated. Especially the models for arriving and departing passengers, as they were estimated on data from 2015 and scaled up to match the 2020 prognosis.

First, we analyse the number of arriving and departing passengers per tram stop, comparing our results to the prognosis. This data is collected and averaged over 100 runs of a simulation of the top performing schedule from section 5.1. The results, including a z-test for significance, in Table 3 show all stops on the track from Central Station to the Uithof P+R to have a significantly higher amount of commuters exiting the tram than expected. This coincides with the significantly higher amount of passengers that board at Central Station, as this results in higher exiting rates at tram stops towards

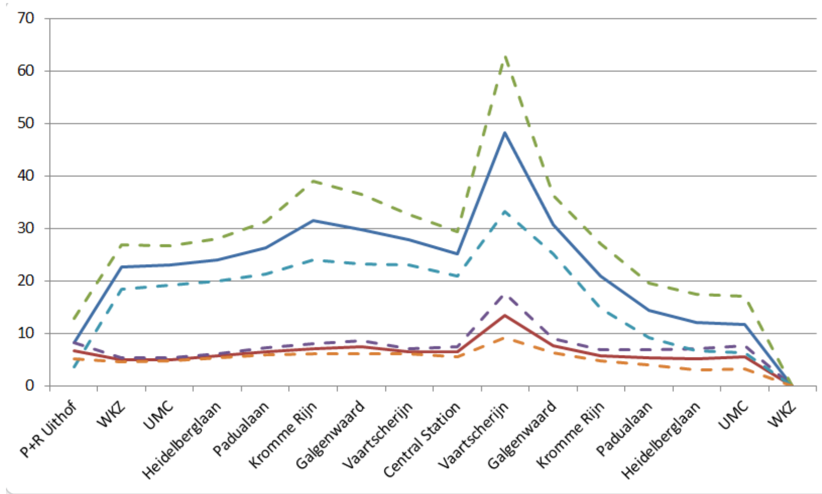


Figure 5: *Left:* Maximum (red) and average (blue) passenger waiting times per tramstop. *Right:* Average fraction of delayed trams per tramstop. Dotted lines represent the standard deviation observed over 100 simulations.

the Uithof P+R. Apart from these discrepancies on the track towards the Uithof P+R, the track heading to Central Station only shows minor deviations from the prognosis. As the simulation is based on slightly higher passenger rates, our results remain valid if more passengers (approximately 260.9 extra hourly passengers at Central Station) show up compared to the schedule forecast in section 2.

Second, run times are validated using average run times per tram stop of over 100 simulations. The results of the z-test are shown in Table 4. Only the stops surrounding Central Station show significant differences from the prognosis. Especially on the track between Vaartsche Rijn and Galgenwaard, the simulated trams run slower than predicted. Thus, tram delays and passenger waiting times can be higher in the simulation than in a real setting that behaves conform the prognosis.

Overall, the estimated models differ from the prognoses on multiple points. This may result in a higher simulated tram frequencies, and higher passenger waiting times and tram delays. Any conclusions about these models and the simulation need to take those possibilities into consideration.

6 Artificial Models

Apart from our estimated passenger arrival and departure rates, based on the data made available by Qbuzz, we also test our simulation on a number of different other passenger rates. These *artificial passenger models*, supplied by Utrecht University [4], contain less detailed information than the estimated model, as they only supply rates per time block (early hours, rush hours, day hours and late hours) instead of per time slot of 15 min. All of the seven models have different characteristics that are explained below. The best schedule for each artificial input file is determined through the same ranking process as described in section 5. In contrast to the method explained in the previous section, the input parameters have a larger range to accommodate for models with higher total passengers. Rush hour and day rates are scaled up to 20 trams per hour, off-peak rates stay the same, as well as values of q.

[4]The models, named 1, 2, 3, 4, 6, 15 and 25, can be found at http://www.cs.uu.nl/docs/vakken/mads/sim_assignment_information.html

Stop	Arriving		Departing	
	Prog.	Avg.	Prog.	Avg.
P+R Uithof	15	15,41 (+-3,7)	15	172,78 (+-16,2)
WKZ	1015	1000,99 (+-33,3)	0	0 (+-0)
UMC	2660	2612,82 (+-49)	0	0 (+-0)
Heidelberglaan	9138	8946,17 (+-112,1)	0	0,09 (+-0,3)
Padualaan	6855	6714,1 (+-90,7)	236	211,06 (+-18,2)
Kromme Rijn	691	690,33 (+-26,1)	31	36,09 (+-6,4)
Galgenwaard	606	601,31 (+-25,3)	265	241,43 (+-16,1)
Vaartscherijn	1261	1251,91 (+-36,7)	544	486,05 (+-22)
Centraal Station Centrumzijde	19994	22409,79 (+-263,4)	21164	20858,32 (+-160,3)
Vaartscherijn	2337	2314,59 (+-52,4)	1735	1898,04 (+-76,3)
Galgenwaard	359	357,21 (+-20,6)	1288	1351,75 (+-57,6)
Kromme Rijn	47	47,22 (+-6,8)	1039	1163,58 (+-42)
Padualaan	10	12,02 (+-3,5)	9672	10733,6 (+-274,5)
Heidelberglaan	8	8,09 (+-3)	5789	6303,38 (+-207,8)
UMC	6	5,75 (+-2,2)	2577	2775,2 (+-98,4)
WKZ	0	0 (+-0)	644	720,73 (+-34,4)

Table 3: Total passengers arriving and departing on the track conform the prognosis (prog) and the average (+- variance) of the simulation rates (avg.). Coloured cells represent simulated values that differ significantly from the prognosis.

Stop	Run time	
	Prog.	Avg.
P+R Uithof	1.833	1.756 (+-0.168)
WKZ	1.3	1.268 (+-0.107)
UMC	1.367	1.287 (+-0.142)
Heidelberglaan	1	0.933 (+-0.069)
Padualaan	1.667	1.664 (+-0.143)
Kromme Rijn	0.983	0.972 (+-0.056)
Galgenwaard	4.050	4.363 (+-0.218)
Vaartscherijn	2.250	2.344 (+-0.154)
Central Station	2.233	2.309 (+-0.164)
Vaartscherijn	4.050	4.323 (+-0.177)
Galgenwaard	0.983	0.974 (+-0.062)
Kromme Rijn	1.683	1.668 (+-0.137)
Padualaan	1	0.940 (+-0.081)
Heidelberglaan	1.433	1.363 (+-0.157)
UMC	1.3	1.262 (+-0.098)

Table 4: Run times in minutes to all stops conform the prognosis (prog) and the average (+- variance) of the simulation (avg.). Coloured cells represent simulated values that differ significantly from the prognosis.

The first input model describes 43,453 daily passengers, roughly the same as the prognosis of 45,000. Moreover, the amount of commuters during rush hours also complies with the forecast. Overall, of all artificial models this is the most similar to the estimated model. Therefore it is no surprise that the best fitted schedules show similarities. As can be seen in Table 5 both favour 11 or 12 trams per hour in rush hours and about six trams per hour the rest of the time. However, due to minor differences in our estimated model and this artificial model, the results are not exactly the same.

The second model also shows similarities to the prognosis, however the total amount of passengers arriving throughout the day is higher; 64,144 people. The amount of people travelling in the expected rush direction is similar to the prognosis. However, there are about twice as many people travelling the opposite direction from the expected stream during rush hour. As trams are already travelling in higher frequencies during rush hour, it is expected they can pick up the extra people on the way back, and no extra rides are needed. Table 5 shows fitted schedules with more trams during day and off (morning and evening) hours, as anticipated by the higher number of total passengers. As expected no extra trams are needed during rush hours.

Artificial model 15 again shares similarities to the prognosis: this time all rush hour traffic is increased by a factor of 1.5. The total number of people travelling in this artificial model is 62,683, roughly 1.4 times the prognosis. As one might expect, the rush hour rates have increased by about 1.5 times compared by the results of artificial model 1 or the estimated model as seen in table 5. In addition, the day rate has increased to accommodate the extra passengers during the day. Maximum waiting times of passengers have increased by one minute, and the average tram delay is almost doubled to 12.7 minutes.

Although having different quantities of total commuters, the artificial models 3, 4, 6 and 25 share one same feature, namely that their day hour rate equals their rush hour rate. Moreover, passengers do not board or exit on stops Kromme Rijn and Galgenwaard and are instead evenly distributed over the other stops, where the same amount of commuters board and exit trams. Thus, the results of these models are expected to differ from the other three artificial models.

The model with the highest total passengers, model 6 with 190,400 commuters, has a rush/day rate five times its off-peak rate. Which means 8000 people try to travel the tram line hourly during work hours. This equals about 19 full tram loads every hour. However, the best fitted schedules in Table 5 show only about 17 trams per hour during rush/day hours. Both the maximum waiting time for passengers, an average of 28.6 minutes over the three best fits, and the average tram delay, 33.8 minutes, are higher than for the previous models.

Both models 3 and 4 have the same arrival rate in off-peak hours. During the rest of the day, however, 1000 passengers more per hour arrive in model 4, making the total arriving passengers in models 3 and 4, 153,800 and 175,800 respectively. Thus, it is no surprise the best fitted off hour frequencies of these two models are comparable and the day rate has increased by about two trams in model 3 compared to model 4. Model 3 shows a maximum passenger waiting time of 72.9 minutes. This has decreased in model 4 to 44.7 minutes. The increase by about 5 trams during rush hours may have lowered the maximum waiting time. However, the average tram delay has increased from 11.3 to 20.6 minutes in model 3 compared to model 4.

Lastly, model 25, having the same basic structure as the previous three models, has 4000 passengers per hour arriving every hour except in the early morning and late evening. Thus, 9 or 10 trams per hour are expected to transport all commuters. In total 95,000 passengers travel the line. From table 5 we indeed see a best fitted day rate of about 10 trams per hour. With a maximum passenger waiting time of 14.6 minutes and an average tram delay of 9.4 minutes, this model has the lowest waiting time and delay of all these four models. As it also has the lowest total amount of commuters and the lowest rush/day arrival rate, this may indicate the line handles lower amounts of commuters better.

Overall, the last four models did not always have an equal day and rush tram frequency fitted, as

Model no.	1st				2nd				3rd			
	q	rush	day	off	q	rush	day	off	q	rush	day	off
1	3	11	7	5	3	12	6	6	4	12	6	6
2	3	11	7	6	3	10	7	6	3	10	7	5
3	3	11	12	8	4	11	11	9	3	11	11	8
4	3	16	14	8	3	17	13	8	3	16	13	8
6	3	16	18	9	3	17	17	9	3	16	20	9
15	4	15	10	7	3	17	8	6	3	16	9	7
25	3	12	11	8	4	11	10	7	3	12	10	7

Table 5: The top three best fitting schedule parameters (turnaround time q and frequencies for rush hour, day hours and early morning and evening) for the artificial models.

one might expect from their structure. Models with high amounts of total passengers, such as models 4 and 6, show a difference of sometimes three trams per hour. This difference might be to make up for the accumulated delay of trams that circle around all day. If both the rush and day frequency were exactly the same with a high amount of trams per hour, trams starting at the morning rush hour will be circling the line until the end of the evening rush hour. During this time, trams can build up large delays and may end up in large queues. Having a difference in day and rush hour tram frequencies can pull delayed trams to the marshalling yard and put new, undelayed trams in the running.

7 Discussion

At the start of 2019, the company Qbuzz will be replacing the current bus system to the Uithof with a tram line. In this report, properties of the new Uithof tram line were estimated by using a discrete time simulation. Our main focus was to find a feasible timetable for the new tram line. By simulation different sets of input parameters, we found a top performing schedule with turnaround time $q = 4$, a rush hour frequency of 12 trams per hour, and day and off-peak rates of 6 trams per hour. This schedule minimised the maximum passenger waiting time to 22.58 minutes over the entire day, the average tram delay at end stations to 7.87 minutes and the number of passengers that were unable to reach their destination to 0. Moreover, the average passengers waiting time for this schedule equalled on average 6.60 minutes, and the maximum tram delay averaged 31.35 minutes. This top performing schedule shows higher frequencies than the predicted best schedule of 11 trams per hour during rush hour, and 3 trams per hour for the rest of the day. As discussed in section 5.3, the deviation in arriving passengers in our model compared to the prognosis, may contribute to about one tram per hour more needed.

Moreover, artificial model 1 shows similarities to the prognosis, and its best fitted schedules are comparable to the top performing schedules of the estimated model. Thus, the schedules could differ from the predicted schedule for other reasons. Of course only having three trams per hour (as predicted) for most of the day, increases passenger waiting times over having more trams per hour. As we rank the fitted timetables on maximum passenger waiting times, these low-rate schedules will not reach high ranks. To establish the reason why twice as many trams are scheduled than predicted, more research has to be done.

The second question, about the capacity of the tram line depends on the chosen schedule. For the predicted schedule, the maximum amount of people able to travel the line exceeded the prognosis of 45,000 passengers by 23,460. The capacity of the top schedule from the simulation exceeded the prognosis by 58,320 passengers. Thus, more than twice the amount of predicted passengers are able to board the line, which is excessive even on a busy day. Therefore, a schedule with lower tram frequency can also be feasible for the Uithof line, however the passenger waiting times will increase in this scenario.

Some flaws of the process are left to be discussed. When estimating the variance based on the acceleration, as in section 4.1, we estimated it on known accelerations from 1000 km/h^2 and up. However, on parts of the track of the Uithof line accelerations occurred of around 600 km/h^2. As we used a polynomial fit the variance of these lower accelerations is estimated too high. Therefore delays can be built up easily, and can accumulate through the day. As a countermeasure, trams with high accumulated delays are sometimes swapped for *new* trams, and trams are not allowed to exceed a run time of the mean plus 1.5 times the variance. Of course, it would be more suited if a better fit was found on the variance and acceleration data. In order to do this, more data of the run times of trams on shorter, busier tracks needs to be accumulated, e.g. including tram lines from other cities.

References

[1] Büchel, Beda, and Corman, Francesco, *Modelling probability distributions of public transport travel time components*, 18th Swiss Transport Research Conference (STRC), 2018.

A Minutes of meeting with Qbuzz

During the meeting with Marcel van Kooten Niekerk from QBuzz there was an opportunity to ask questions about various facets of the tram simulation assignment. Van Kooten Niekerk started off by telling about the overall requirements of the tram. The trams will run in doubles, can carry 420 passengers in total and have a maximum speed of 70km/h. During a full day, the number of trams available is non exhaustive, however, there is an outline on how many are expected to run in each time slot:

6:00-7:00 at least one tram every 15 minutes
7:00-19:00 as many as possible (e.g. every 5 minutes)
19:00-21:00 at least one tram every 15 minutes

To find the right balance between short waiting times for the passengers and running full trams, we are expected to create multiple scenarios. Management will then decide between the presented schedules. When met with long delays, it is best not to deploy extra trams according to the schedule, but tot stop some rides from running. This measure will prevent trams for lining up in long queues, with passengers waiting inside. In this simulation we are not to simulate unforeseen defects or traffic accidents that can cause such delays in an instant.

Moreover, van Kooten Niekerk talked about the end stations of the tram. All of the trams are deployed from the end station at the Uithof, as this station has a marshalling yard. However, the rest of the layout of the end stations is the same: a single platform in the middle of two tracks and a system to switch tracks in front. When parked at the platform, the time it takes for a tram driver to change the direction of the cars is at least 3 minutes.

Furthermore, some details were given about what happens at the stops in between the end stations. Whenever there is a queue of trams at a stop, it takes 40 seconds for the next tram in queue to line up at the platform after the current tram has left. Then it will take some time for the passengers to get on and off. Van Kooten Niekerk handed us the distribution for this so called dwell time: a gamma distribution where $k = 2$ and mean $= 0.8 \cdot d$, with $d = 12.5 + 0.22 \cdot passengers_{on} + 0.13 \cdot passengers_{off}$.

Lastly van Kooten Niekerk pointed out some files on the website that are available to use to estimate, for example, the run time between stops and the amount of passengers waiting at stops to get on the tram.