Evaluation of Dynamic Bus Lanes in Zurich

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Abbreviations

DBL	Dynamic bus lane
IBL	Intermittent bus lane
BLIP	Bus lane with intermittent priority
TSP	Transit signal priority

Master Thesis in Civil Engineering

Evaluation of Dynamic Bus Lanes in Zurich

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Abstract

In intra-urban environments, buses flowing in mixed traffic with cars are often subject to delays caused by congestion. To avoid unreliable bus services, dedicated bus lanes have been established in many cities, including Zurich. By separating buses from general traffic, they help minimize public transport delays, but at the same time capacity is taken away from car traffic. Recent research proposed the concept of dynamic bus lanes to better exploit urban roads: A lane is dedicated to buses only at the very moment when they run. In the time segment between two buses, all lanes are accessible to cars. The master thesis at hand prepares the implementation of dynamic bus lanes in the city of Zurich by investigating the interactions of buses and cars. By means of videotaping, data was collected at Winzerhalde, where a dedicated bus lane is made accessible to general traffic. Lane occupation, delays, flows, and capacities were calculated in relation to bus presence and compared at up and downstream locations. We found that the bus exerts practically no influence on general traffic when it is led in its own dedicated lane. In contrast, cars are affected in terms of delays and capacities when they flow in mixed fashion with buses. The smoothing effect of the separated bus lane falls away, so capacity is not doubled by making it accessible to cars. However, even when driving behind a bus, the car-carrying capacity of two lanes in mixed road use is higher than that of one lane next to a dedicated bus lane. Given that the share of time during which a bus is present is rather small, depending on the bus frequency, dynamic bus lanes are preferable to dedicated bus lanes from a car's point of view.

1 Introduction

In urban environments, where buses and general traffic (i.e. cars) operate in mixed fashion, buses can often encounter delays due to their interactions with cars. Bus operations can be impeded by car congestion, resulting in unreliable and slow bus services. This can also lead to reduced productivity of bus services and an increase in costs per passenger, while shrinking the revenues for bus operators. On the other hand, buses that stop frequently can interfere with the flow of cars. Overall, these interactions can reduce capacity for both cars and buses. One commonly used solution to mitigate the negative effect of car and bus interactions is to dedicate lanes to bus-use only. These lanes spatially decouple private and public transport systems and can provide a means for buses to bypass car queues and also eliminate conflicting movements between cars and buses. The result can be reduced total person hours of travel, since buses typically have higher passenger occupancy.

However, this approach may not always be feasible due to limited space. Even when feasible, if bus flows are low, dedicating a lane to bus-use only by converting an existing mixed-use lane could reduce car discharge flows from critical locations and lead to excessive car delays. Overall, this could increase the total person hours of travel due to the penalties experienced by car users. Moreover, the negative effects of dedicating more space to transport on the quality of the urban environment in general and the public space in particular are often not acceptable.

Buses only need a reserved space (their own lane) at the exact moments when they run, i.e. about 10-20 times per hour for about half a minute each time. So, giving priority to buses can still be achieved by converting mixed-flow lanes to dynamically shared car and bus lanes. By means of telematics, a right of way for buses can be provided at the time needed, without converting the lane into a bus-only facility.

Like all urban areas, Zurich encounters high traffic volumes. In order to prevent unacceptable public transport delays due to congestion, several lanes throughout the city are dedicated to buses. At critical bottlenecks, however, dedicated bus lanes reduce car-carrying capacity and increase congestion and air pollution. Converting those lanes into dynamically used bus lanes could improve traffic conditions without affecting the service quality of public transport too much.

The theoretical concept of dynamic bus lanes has been researched by various scientists. But there is still not much knowledge about the elementary interactions of public transport buses and cars. The goal of this work is to improve our basic understanding of how buses and general traffic affect each other in urban areas, whereas the focus lies on the influence that buses exert on cars. The study field is limited to the city of Zurich, and the results are not universally valid, but depend on local circumstances and driving behaviour. The findings serve to assess feasibility, benefits, and downsides of dynamic bus lanes in the city of Zurich. Various parameters regarding traffic flow will be examined empirically and related to the influence of buses. Data collected by means of videotaping at selected locations in the city of Zurich will be the basis for research.

2 Literature Review

2.1 Dynamic Bus Lanes

Viegas and Lu (2001) first analyzed the concept of intermittent bus lanes (IBL). They introduced a bus priority system for arterials where there is no lane dedicated to buses at all times, but only when there is actually a bus approaching. As the bus is detected upstream, longitudinal lights in the pavement flash on, and the status of one lane of the road is changed to that of a special bus lane. After this moment, vehicles already driving in this lane can stay or merge to other lanes, but no vehicles are allowed to change from other lanes into the special lane. As the bus proceeds, the lights are successively turned off, so that the lane space behind the bus is in normal lane status and can be entered by vehicles again. Since vehicles ahead of the bus are not forced out, the bus could be delayed in a downstream congestion (e.g. due to traffic signals). To avoid this, the moment when the lights turn on should be chosen with the possibility of a downstream queue in mind, which would have to be able to discharge in time. In addition to this, traffic signals may have to be adjusted if the lane cannot be emptied during one cycle.

By means of kinematic wave theory, Viegas and Lu developed and examined the IBL model and integrated it into an existing urban traffic control system. Assuming a signalized intersection with an IBL on one arm, they analytically determined bus delays for different traffic signal settings. Travel time losses of vehicles were calculated for various block lengths, arrival flows, cycle lengths, and time spans between start-up of the IBL signal and bus entrance. They typically increased with arrival flow and block length.

The IBL concept was implemented in Lisbon in 2005 and 2006 and documented by Viegas, Roque, Lu and Vieira (2006). The installation was performed along 800 meters of one road by eliminating illegal parking. During the six months of the demonstration, the impacts on bus travelling times and on general traffic flow conditions were evaluated. For the average bus speed, the results from the real-world application revealed an improvement of 10% to 15% attributed to the IBL system. The analysis of general traffic flow, speed, and queue accumulation did not show any significant change in the overall pattern.

Eichler and Daganzo (2006) proposed and analyzed an IBL variant they called bus lane with intermittent priority (BLIP). Unlike IBL, BLIP forces vehicles ahead of the bus to leave the bus lane. Thus, traffic signals would not have to be adjusted in order to clear the queues ahead of the bus, which means that the side streets’ capacities would not be reduced.

Eichler and Daganzo (2006) interpreted the bus as a moving bottleneck that reduces the roadway by taking away one lane and that changes the traffic state, as Fig. 1 shows. V_b denotes the speed of both the bus and the shockwave between restricted (minus one lane) but free-flow state D ahead of the bus and "congested" but not restricted state U after the bus. Taking into account the presented diagrams in Fig. 1, Eichler and Daganzo found several expressions of car delays and capacity reductions which were found to be minor. The application of BLIP systems or BLIP combined with transit signal priority (TSP) was qualitatively defined as suitable for demands close to q_D. For demands less than 80-90% of q_D, dedicated bus lanes were deemed to be applicable without causing great delays to general traffic, while for demands larger than 120% of q_D, pure TSP was said to be reasonable.

The formulas obtained by kinematic wave theory assume that the lane changes do not reduce the saturation flow per lane, which is optimistic. Furthermore, the system is assumed to be homogenous, so kinematic waves make sense.

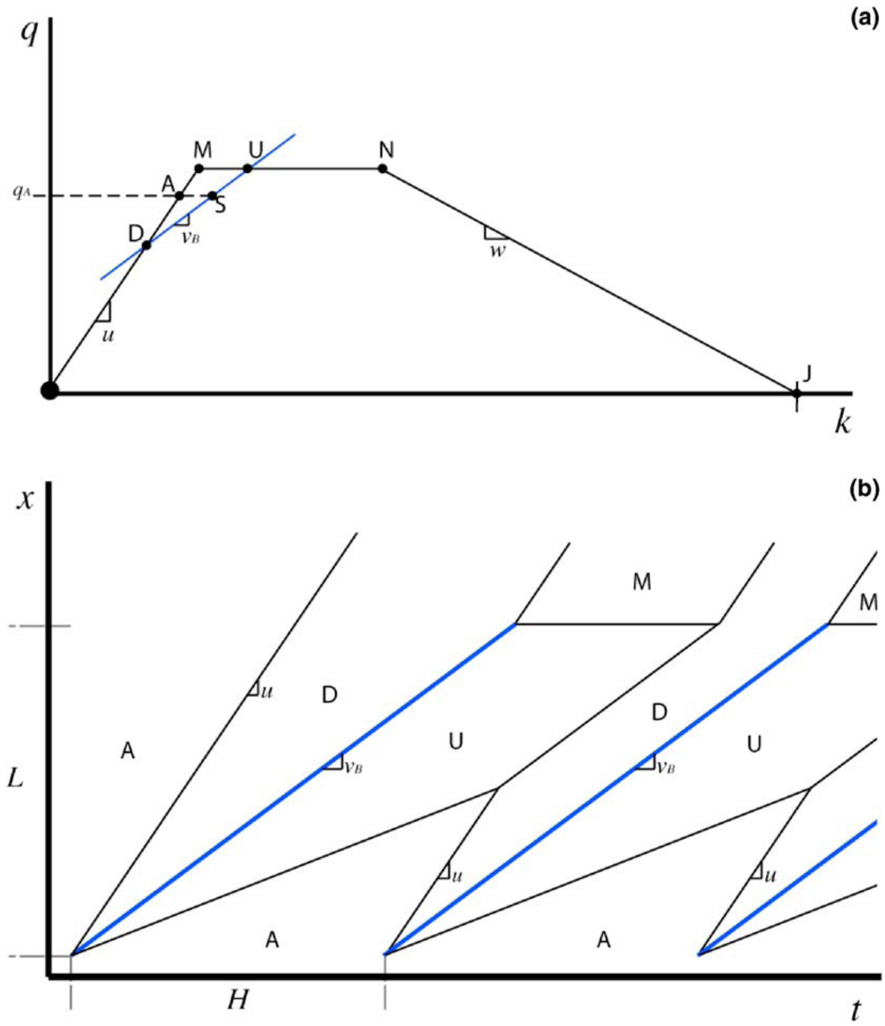

Fig. 1: Macroscopic diagrams for a multi-bus BLIP system: a) fundamental diagram; b) time-space diagram with multiple buses [Source: Eichler and Daganzo (2006), 738]

Guler and Cassidy (2012) evaluated special types of dynamic bus lanes, involving ordinary dedicated bus lanes over the major part of the network. However, at select bottlenecks, the underused bus lane is opened to general traffic in order to prevent capacity squandering and added delays. Unlike IBL and BLIP, the strategy examined by Guler and Cassidy is not intended for use on arterials, but for facilities with infrequent bottlenecks.

Domains of application were determined both for active bottlenecks and for queued bottlenecks. The upper bounds on bus flow for which a shared lane provides greater car-carrying capacity in the bottleneck depend on the capacity loss due to disruptive merging at the bottleneck's downstream end or due to disruptive vehicular diverging at its upstream entrance. It is believed that the proposed lane-sharing idea would work effectively in most cities under the precondition that field studies are conducted to measure the above-mentioned merging effects.

2.2 Smoothing Effect

Various studies have shown that in real freeway traffic, carpool lanes are not as damaging to overall capacity as one would expect, even if they are underutilized. Cassidy, Daganzo, and Jang (2009) confirmed in a spatiotemporal analysis that the presence of a carpool lane can diminish disruptive vehicle lane changes, so that bottleneck flows are increased. The so-called smoothing effect has so far been observed in freeway traffic with carpool lanes, but could as well occur in city networks with dedicated bus lanes, since segregating different vehicle classes should lessen capacity reductions due to lane changing even more. If this were the case, dedicating one or several lanes of a roadway to buses only, the overall capacity could be greater than if all lanes were used by general traffic.

3 Research Approach

Dynamic bus lanes have been demonstrated in field experiments, but never implemented permanently in existing roadway networks. The studies referred to in section 2 base on kinematic wave theory and assume homogenous conditions. Buses are modeled as moving bottlenecks with speed v_B, but specific interactions between buses and cars are not considered. The analytical approach neglects several real-world effects that could occur in networks where buses operate and that have a significant influence on the success of dynamic bus lanes. To measure and quantify these behavior characteristics, field studies have to be carried out.

Although there are still no permanent dynamic bus lanes in operating city networks, nearly all their elements and settings can be found in existing systems with established bus operating strategies. Conclusions about dynamic bus lanes can thus be drawn from examining car delays and flows at car-bus interfaces in real-world networks. Table 1 shows possible analogies between the bus operating strategies.

Table 1: Analogies of dynamic bus lane settings in common bus strategy situations

N°	Dynamic bus lane	Common bus operating strategy	
	Setting/situation	*Location*	*Point in time*
1a)	Access to shared lane is prohibited for general traffic when bus is approaching (IBL)	Dedicated bus lane next to general use lane	Any/ moment when bus approaches[1]
1b)	Access to shared lane is prohibited for general traffic & vehicles are forced out of lane when bus is approaching (BLIP)	First signal that advises vehicles of the shared lane's ending (e.g. arrow road marking)	Any (independent of bus arrival)
2)	Bus lane is open for general traffic after bus has passed	Signalization of special bus lane ends, but lane continues as shared lane	Moment when bus leaves the signalized bus lane
3)	General traffic is flowing behind the bus	Shared lane (at bus stop locations and in between)	Moment when bus is passing
4)	No bus is present; bus lane is freely accessible to general traffic	Shared lane	Time span between two buses

The following parameters are relevant to understand car travel times in relation to different bus operating strategies:

1a) Access to shared lane is prohibited for general traffic when bus is approaching (IBL)

- Delays due to disruptive vehicular merging
- Fraction of vehicles that leave bus lane
- Flow increase/decrease (smoothing effect vs. capacity reduction due to lane restriction)

1b) Access to shared lane is prohibited for general traffic & vehicles are forced out of lane when bus is approaching (BLIP)

- Delays due to disruptive vehicular merging

[1] The behavior of vehicles already flowing in the bus lane ahead of the bus cannot be represented perfectly, since there is no common bus operating situation where vehicles cannot enter a lane from adjacent lanes, but the vehicles already present in that lane are allowed to stay there. With common bus strategies, those vehicles are not advised of the approaching bus by flashing lights, whereas this signal could influence the behavior on the "bus lane". However, the effects of the non-accessible bus lane on adjacent lanes can be observed.

- Flow increase/decrease (smoothing effect vs. capacity reduction due to lane restriction)

2) Bus lane is opened for general traffic after bus has passed

- Delays due to disruptive vehicular diverging
- Fraction of vehicles that diverge into bus lane and drive behind the bus
- Flow distribution to all lanes
- Flow increase/decrease (smoothing effect vs. capacity reduction due to lane restriction)

3) General traffic is flowing behind the bus

- Flow distribution to all lanes
- Delays due to lane changing

4) No bus is present; bus lane is freely accessible to general traffic

- Flow distribution to all lanes
- Delays due to lane changing

Of these configurations, nos. 1) and 2) are the most interesting to gain insight into the operation of dynamic bus lanes, because they extend the common bus strategy situations 3) and 4). As explained above, the IBL setting 1a) cannot be observed in common bus strategy configurations. However, since one can expect that the BLIP system will cause more damage to car traffic than IBL, it makes sense to investigate only setting 1b). Thus, to proceed, the analysis concentrates on two main configurations:

A) Bus lane is opened for general traffic after the bus has passed

B) Access to shared lane is prohibited for general traffic & vehicles are forced out of lane when bus is approaching

4 Data Collection Set-up

4.1 Investigation Site

For the observation of the above listed parameters, a suitable investigation area had to be found. In the following sections, the chosen location in the city of Zurich is presented and discussed.

4.1.1 Situation A: bus lane is opened for general traffic after the bus has passed

Situation A, where the bus lane is opened for general traffic after the bus has passed, is represented several times in Zurich. The listing of all possible settings can be reviewed in appendix A 1 (pp. A-1 ff.).

The chosen setting is located in Zürich Höngg (a district of the city of Zurich) near the Werdinsel (a small island in the district, between the river Limmat and an artificially arranged canal), where the Winzerstrasse (western arm, see Fig. 2) discharges into Europabrücke (southern arm). The bus is conducted in its own lane up to the bus stop Winzerhalde. After that, general traffic wanting to turn right is allowed to move into the rightmost lane. Winzerhalde is a unique setting, because there is another right-turning lane next to the abolished bus lane. Thus, in contrast to most other similar locations in Zurich, right-turning vehicles are not forced to change lanes. Furthermore, the next intersection is located at a respectable distance downstream of Winzerhalde. So, we can assume that lane changes are effected voluntarily.

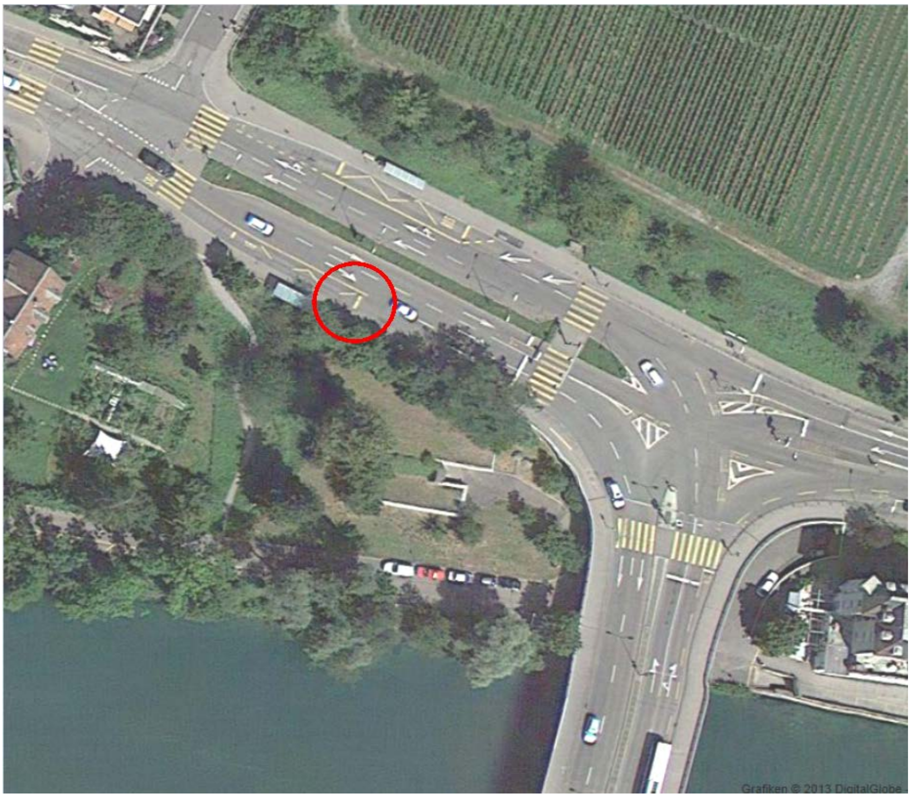

Fig. 2: Situation A at Winzerhalde [Source: Google Earth]

Four bus lines operate in this section (see also appendix A 3, pp. A-11 ff.):

- Line 80;   9 buses per hour
- Line 89;   4 buses per hour
- Line 304;   2 buses per hour
- Line 308;   2 buses per hour

The high frequency of approximately 19 buses per hour (i.e. a bus every 3 minutes) creates many interaction situations for analysis. However, Winzerhalde provides some complicating elements that have to be considered:

- The bus lane ends right after the bus stop (see Fig. 3, orange area). So, when the bus interferes with the general traffic, it is accelerating. Drivers may react differently to a stopping bus than to a moving one.
- There is a traffic light right after the abolishment of the bus lane (see Fig. 3, red line). The bus-car interactions have to be examined according to the phase.

- Another traffic stream from the eastern arm of the intersection (Am Wasser) enters Europabrücke (see Fig. 3, blue arrow). Thanks to the traffic light, it does not run at the same time as the stream from Winzerstrasse. Still, the analysis downstream of the intersection on Europabrücke must account for the vehicles from Am Wasser in order not to confuse the two streams.

- The speed limit is raised from 50 km/h to 60 km/h on Europabrücke (see Fig. 3, dashed black line). As a consequence, capacity could increase.

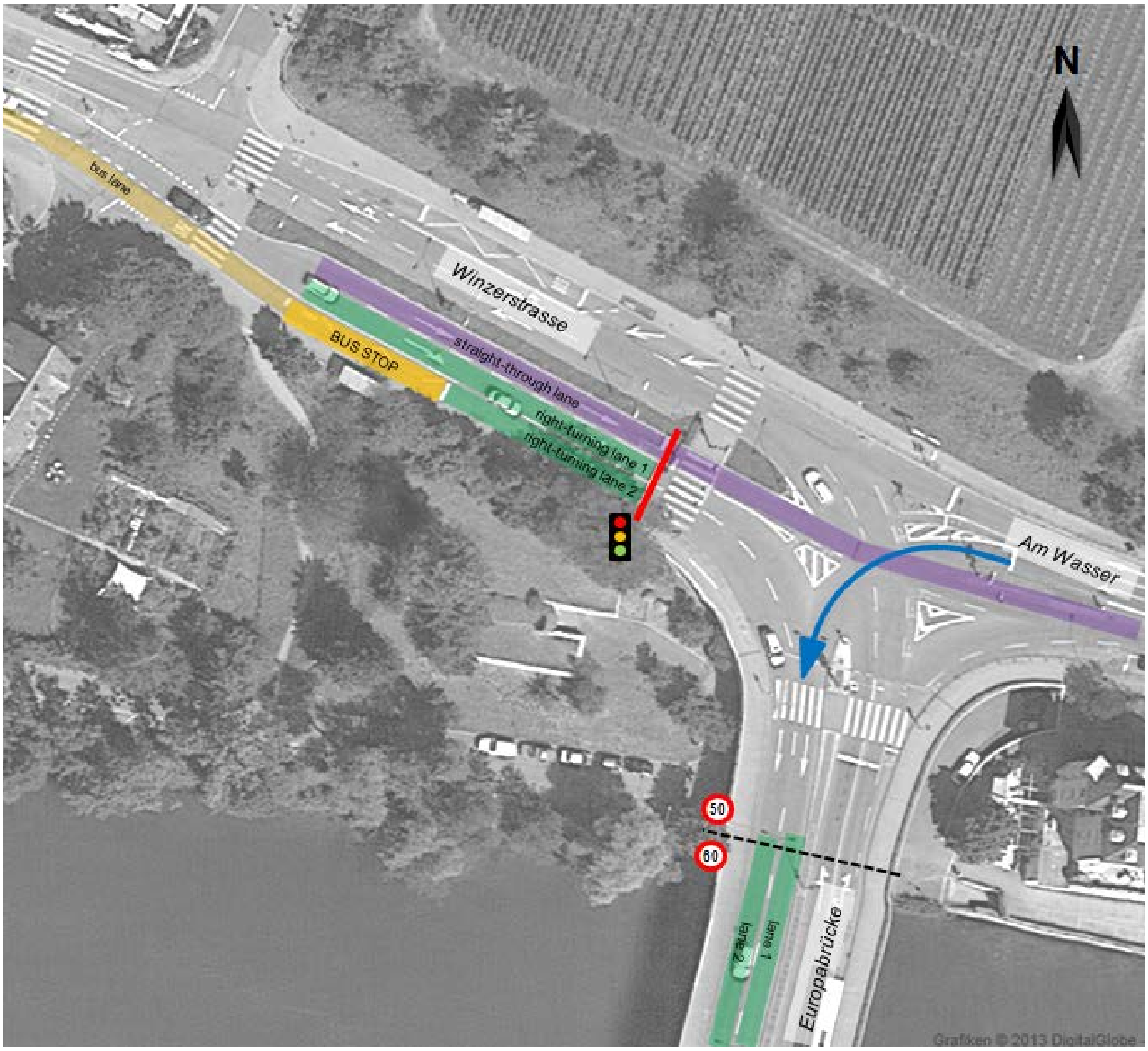

Fig. 3: Plan of site Winzerhalde [Source: Google Earth, edited]

4.1.2 Situation B: Access to shared lane is prohibited for general traffic, and vehicles are forced out of this lane

Configuration B (the situation where a shared lane is closed for general traffic and vehicles are forced out of this lane) can be observed at several locations in the city of Zurich. For various reasons, however, they are all not suited for the collection of significant data. One critical problem is common to all inspected settings: Drivers who are familiar with the area avoid the later converted lane. Driving behavior in Switzerland or in Zurich in particular seems to avoid last-minute lane changes which could inconvenience other vehicles or cause delays. As a consequence, the lane that becomes a dedicated bus lane is practically not used, so that no investigation can be carried out.

All inspected locations and their disqualifications are listed in appendix A 2 on pages A-8 ff.

4.2 Concept

The data was collected by means of video records. Cameras were installed up and downstream of the road section whose impacts were to be investigated. Time synchronization between all devices was essential. The records were evaluated subsequently.

In order to determine the set-up of the data collection, it was essential to understand the analysis procedure first.

For the assessment of flow, vehicles per lane and time interval were counted manually. The flow shifts between up and downstream locations could then be calculated. Alternatively, the flow could be derived from the time headways.

To examine delays, queuing theory was applied: At the upstream location, vehicles were registered with their exact arrival time. The same procedure was executed downstream. In a diagram where the axis of abscissas is time and the axis of ordinates is the number of vehicles, input and output curves were drawn. The output curve was then offset by the free-flow travel time between the two locations, so the area between the two graphs could be interpreted as total delay.

For both flow as well as delay analysis, possible branches between the recording locations had to be considered. Most likely, additional cameras would have to be placed there to register the vehicles entering or leaving the road. In the case of Winzerhalde, there was no branch immediately downstream of the bus lane’s end.

According to section 3, the following effects could be expected and were measured:

- Flow increase/decrease due to the abolishment of the dedicated bus lane and the presence of a bus
- Delays and speed change due to the abolishment of the dedicated bus lane and the presence of a bus
- Lane changing behavior: Fraction of vehicles that change to the former bus lane and corresponding location

To estimate the influence of the passing bus, all mentioned parameters were measured continuously and then assigned to periods when a bus was present or absent, in order to compare the results. For this purpose, the moment when entered and left the monitored section had to be registered exactly.

As mentioned in section 4.1.1, there is another traffic stream going south on Europabrücke. The stream from the east arm Am Wasser had to be separated from the stream of interest; the one coming from Winzerstrasse. One possibility was to meter the flows on Europabrücke continuously and afterwards assign them to either stream. This could be done by registering the green signal times in the Winzerstrasse arm and allocating the downstream vehicles to the respective stream. To save evaluation time, however, it made more sense to preliminarily exclude the vehicles coming from Am Wasser from the analysis.

Another concern discussed in section 4.1.1 was the signal light, which intrudes on free-flow driving behavior. However, in the IBL as well as in the BLIP systems presented by Viegas and Lu (2001) and Eichler and Daganzo (2006), respectively, intersections signalized by traffic lights are components of the discussed settings. Thus, data was collected continuously, and its analysis was thereafter carried out under consideration of the signal light.

4.3 Time Period

At times of low demand, the impacts of the bus on general traffic flow are difficult to observe. The cars as well as the bus can change lanes easily without interfering too much. Data collection would take a lot of time, since buses would often pass in the absence of other vehicles. What’s more, the benefits of dynamic bus lanes come into effect mainly when demand is high. Therefore, a time period with more congestion would have to be chosen.

A visual inspection of Winzerhalde unveiled that traffic congestion was higher in the morning hours than in the afternoon and evening. We therefore collected data during the morning peak from 6:45 a.m. to 8:00 a.m.

4.4 Video Camera Set-up

Three video cameras were installed on site. One was placed upstream of the intersection to measure the reference flow there. By choosing the right location, camera 1 would have to register the bus arrivals and departures at the bus stop equally. It was placed on the center island of the street (see Fig. 4). Had it been installed on the sidewalk, the bus would have blocked the view during its entire stop time.

The second camera was installed on the center island a few meters upstream of camera 1 (see Fig. 4). It was important that it capture both right-turning lanes and the traffic light itself, so that signal times could be registered. Camera 2 was essential for the monitoring of the lane changes. The downside of location 2 is that vehicles in the straight-on lane, especially trucks, can block the sight on the two right-turning lanes. By placing the camera as far upstream as possible, this problem was evaded, as long as the queue on the leftmost lane did not become too long.

Camera 3 was located downstream of the intersection, where vehicles have already accelerated to free-flow speed (see Fig. 4). Flows on both lanes were measured there, and delays were evaluated. In addition, the moment when the bus passed had to be registered to distinguish time periods influenced by the bus. Camera 3 was placed upstream of the sign which announces the speed limit raise. Thereby, capacity analysis could be carried out without considering different speed limits.

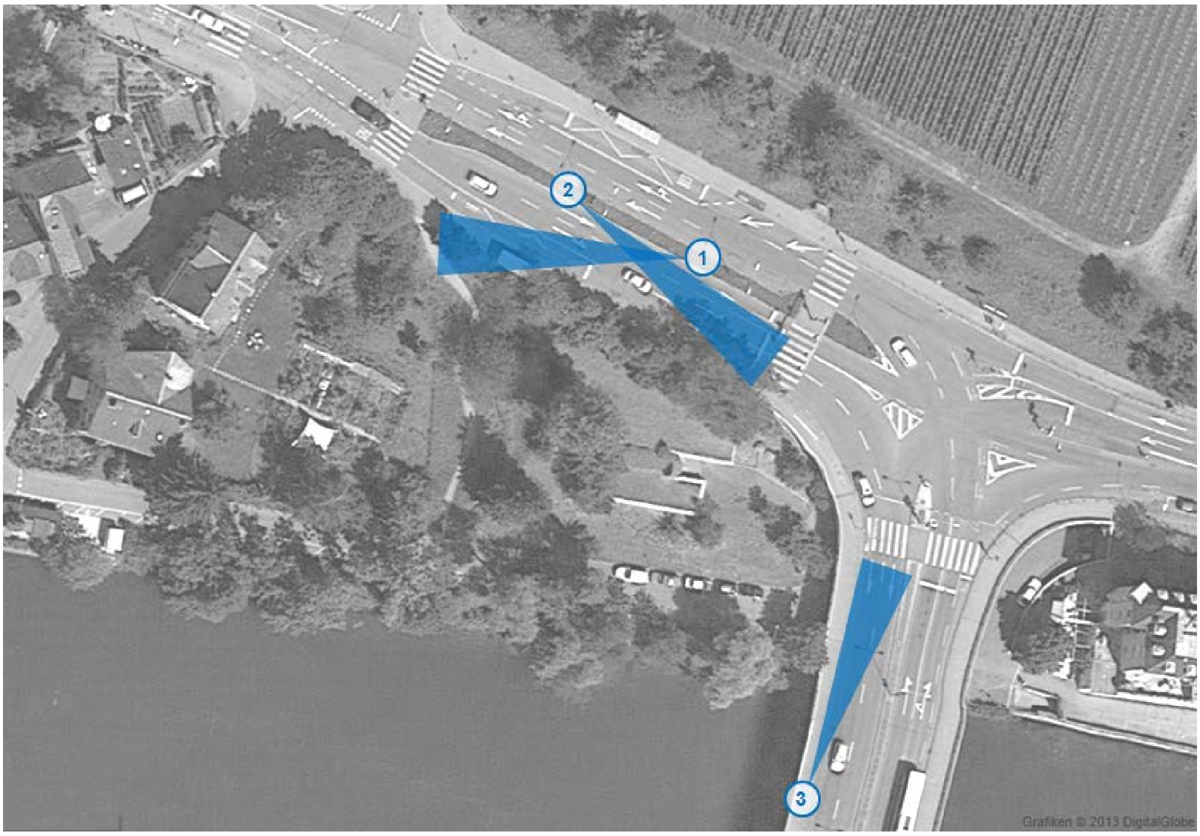

Fig. 4: Video camera locations

5 Data Extraction

The collected data from the three cameras C1, C2 and C3 was extracted with the aid of a macro in Microsoft Excel. An easily recognizable landmark was chosen for each location (see red bars in Fig. 5), and whenever a vehicle crossed those lines, the exact point in time was recorded. At C2 and C3, the extraction was carried out separately for the left and the right lane. Motorbikes and bicycles were excluded from the analysis, because their driving behavior is much different from that of cars. Each vehicle was numbered and then identified manually in all three videos. Very careful processing was essential, because the correct travel times and delays could not be calculated, if a single car in the dataset of one camera was missing. Certain time periods in the video of C2, where the intersection is hidden by vehicles on the leftmost lane, were excluded from the analysis. The same had to be done for a few phases in C3, during which a downstream congestion distorted flow and travel time results. The dataset included information of 1’270 vehicles, 22 buses, and 65 traffic light cycles.

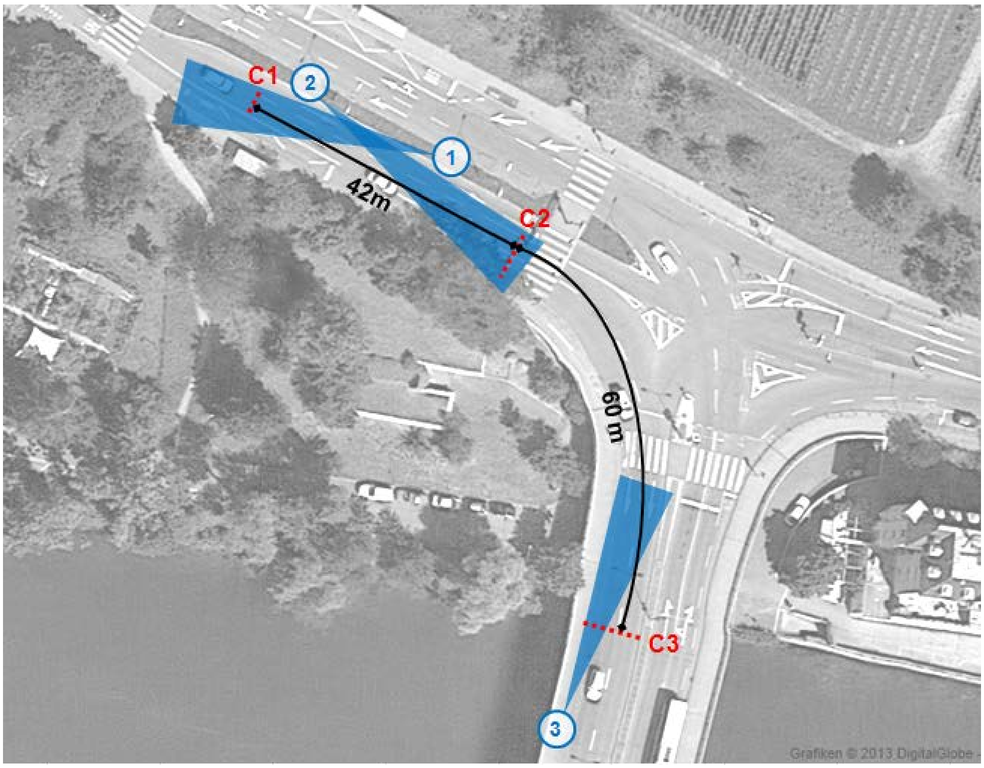

Fig. 5: Landmarks

As a second step, the exact point in time when the bus passed the three lines was recorded and for each car, a parameter describing the bus influence was set. The first vehicle within the bus influence phase crossed the line of C1 right after the bus. Then it overtook the bus, which halted at Winzerhalde bus stop. The position of each vehicle respective to the bus was recorded at location C2. Cars which crossed the C2-line ahead of the bus received the notation “in front of bus”, those which passed it right next to the bus were marked “next to bus”, and every car that went across the C1-lane as long as the bus was still visible (i.e. before it had turned right) were tagged “behind bus”. The same was done for location C3.

The data was completed by numbering the cycles, which enabled the identification of the first vehicle of every new cycle. With this information, virtual departure curves for C2 were drawn: Since there is a traffic light at C2, delays at this location vary significantly. They are large at the beginning of a new cycle, after cars had to wait for the whole red time, and much smaller towards the end, when vehicles pass C2 at free-flow speed. If delays caused by buses were to be analyzed, the effect of the traffic light on the delays had to be eliminated. This was done by employing the concept of a “virtual departure curve”. For every vehicle n registered at C2, an algorithm checked whether it was the first car of a new cycle.

(1) $c_n \neq c_{n-1}$

If this was the case, its virtual departure time (“vdt_n”) was set equal to its actually recorded departure time (“adt_n”). We assumed that at the beginning of a new cycle vehicles would flow at capacity with headways of 2 seconds each. In a 2-lane-road, as we have it at C2, the headway of the cars at capacity is 1 s. The free-flow travel time between C1 and C2 is 42 m divided by 50 km/h equal to 3 s, so the free-flow departure time at C2 (“$ffdt_n$”) equates to the arrival time at C1 plus 3 s.

Now the actual departure time at C3 of every car was analyzed, to see whether it was flowing at capacity or not. The second test checked whether the actual departure time at C2 (“adt_n”) exceeded the free-flow departure time (“$ffdt_n$”).

(2) $adt_n > ffdt_n$

This would mean that the car had to decelerate while approaching C2. However, decelerating doesn’t automatically imply that the car discharges at capacity. Another test was needed. According to our assumption that vehicles at capacity discharge with a rate of 1 vehicle/second, the free-flow departure time should not exceed the virtual departure time of the previous vehicle (“vdt_{n-1}”) by more than 1 s.

(3) $vdt_{n-1} + 1s > ffdt_n$

If both those conditions were met, the respective vehicle would have been discharging at capacity, and its virtual departure time was set vdt_{n-1} +1s. If only condition (2) was fulfilled, then the virtual departure time was defined equal to $ffdt_n$, and the capacity parameter was set 0. The same was done, if both requirements (2) and (3) were not met. The whole algorithm is illustrated in the flowchart of Fig. 6.

Of course the results had to be controlled manually in order to eliminate inconsistencies. Especially the capacity parameter can be wrong, because buses don't appear in the data as part of the traffic flow. At the time when the bus passes, there is a time gap in the departure curve which the algorithm could interpret as the end of the capacity state. By checking the values by hand, these errors could be eliminated.

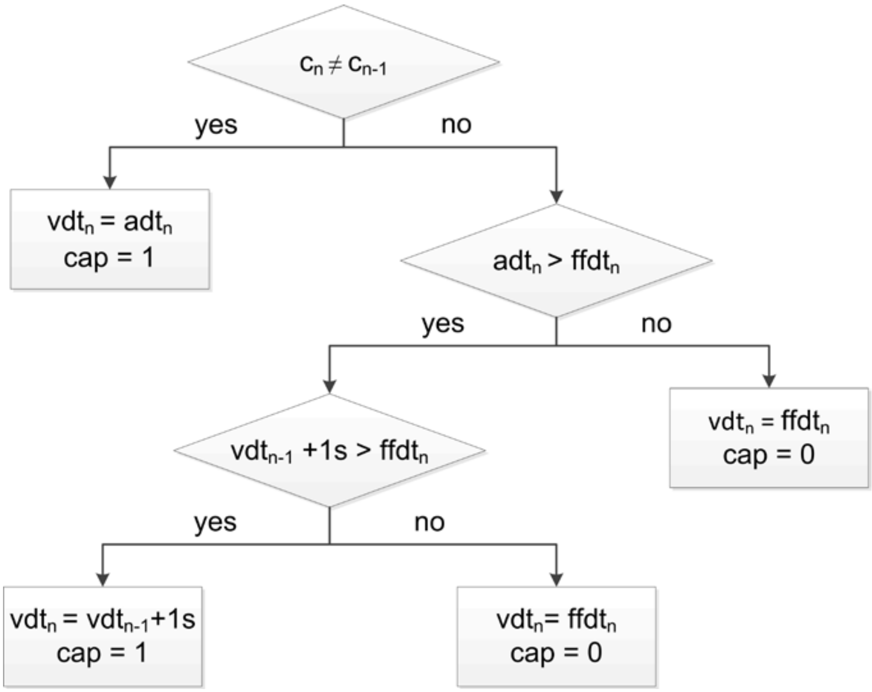

Fig. 6: Algorithm for capacity and virtual departure

Having calculated the virtual departure times, a detailed queuing diagram including arrival curves at C1, actual and virtual departure curves at C2, and departure curves at C3 could be plotted (see Fig. 7). Likewise, the beginnings and endings of the bus' influence were pictured.

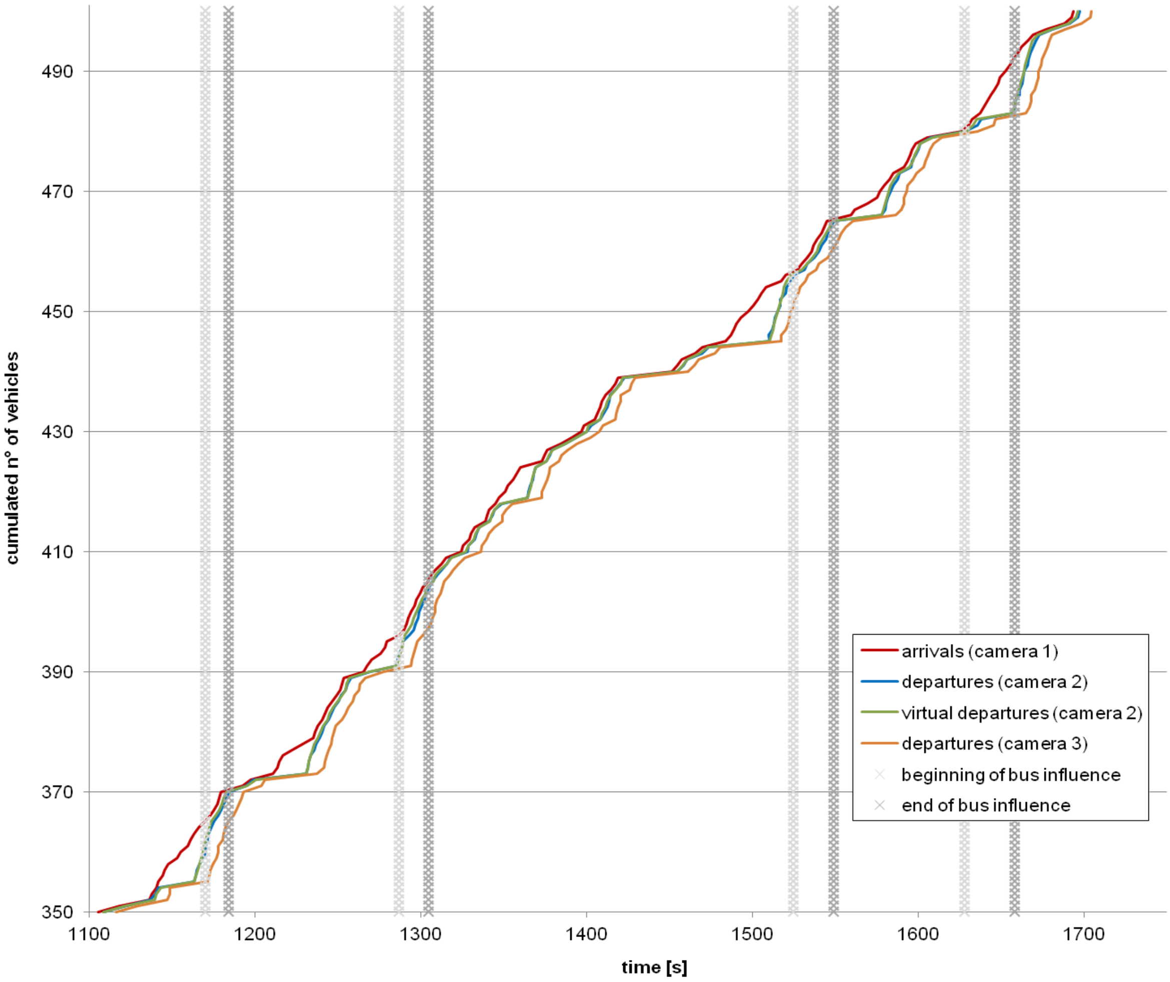

Fig. 7: Queuing diagram (vehicles n° 350-500)

Fig. 8 illustrates the concept of the virtual departures in more detail. The relatively steep sections of the green and blue curves display the capacity periods right after the signal turns green. The almost horizontal sections picture the phase when the light is red. In between, there are periods when vehicles drive more or less at free flow. Inside the grey vertical lines the cars flow under the influence of a bus. In Fig. 8, the actual departure curve and the virtual departure curve at C2 diverge in this time span, which can be interpreted as additional delays due to the bus' presence.

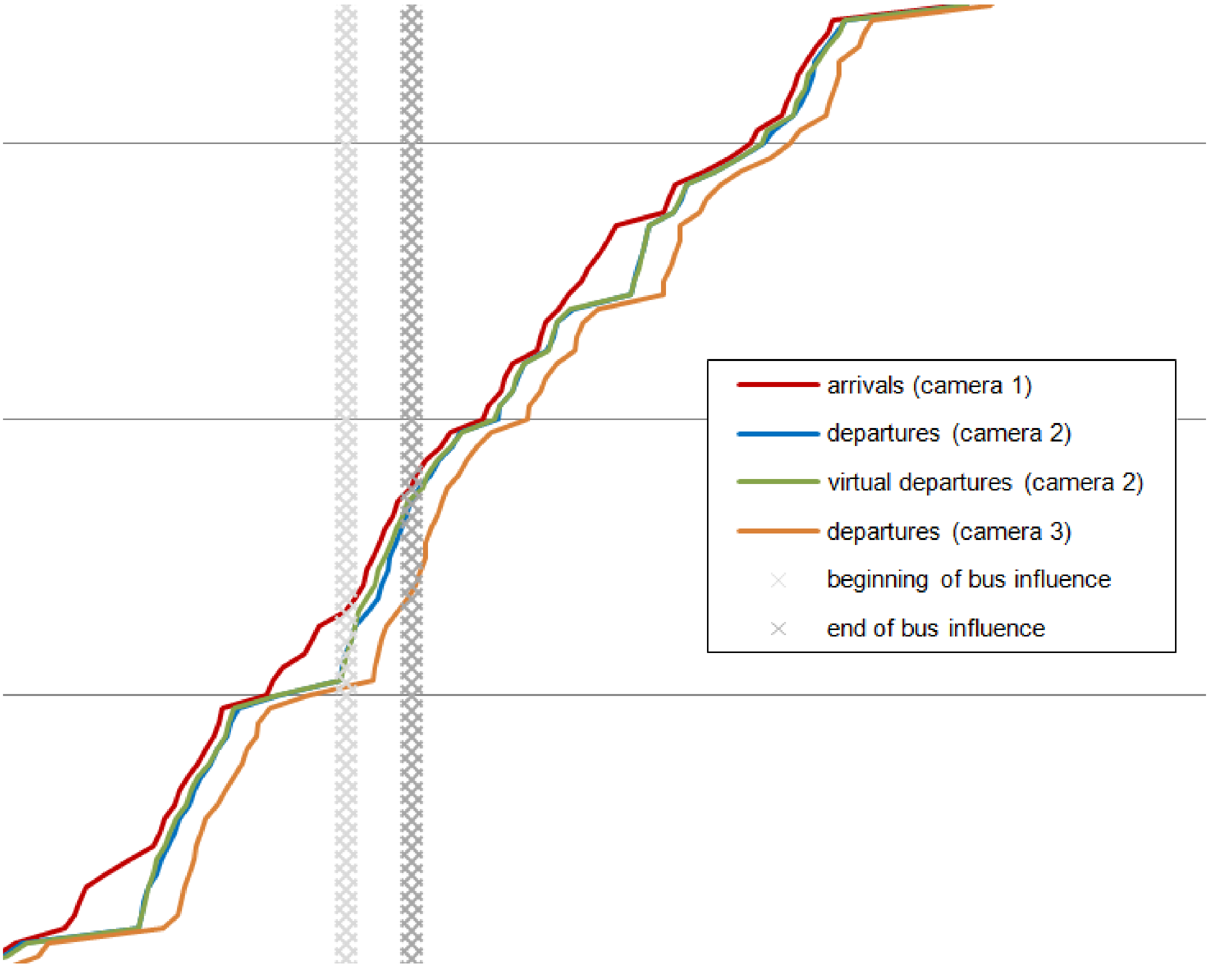

Fig. 8: Detail of queuing diagram

6 Results

In the following chapters, the collected and preprocessed data are analyzed and interpreted. For all essential results, t-tests were carried out to make statements about their statistical significance. A significance level of 95% was employed. The tests can be found in appendix A 4 and A 5 (p. A-15 ff.).

6.1 Lane Choice

At location C2, the former bus lane is made accessible to general traffic. Drivers are free to change to the right lane or stay in the left lane. One can expect that at capacity, when there is no bus present, the lanes will be charged more or less equally. Under a bus' influence, there will be less diverging in order not to disturb the bus or not to be delayed by the bus, respectively. The drivers' lane choices as a function of different parameters were analyzed.

6.1.1 Lane choice at location C2

Fig. 9 shows the proportions of vehicles in either lane relative to the position of the bus without considering the flow state. As expected, in the absence of a bus, the utilization of the left (48.8%) and the right lane (51.2 %) is almost balanced. The right lane is used less often by the vehicles driving ahead of the bus (44.9%). Probably, some drivers want to be sure not to block the following bus and thus stay in the left lane. The cars next to the bus naturally flow in the left lane, while the following drivers mostly choose the left lane as well (73.9%). As the buses usually go slower than other traffic, because they have to halt at bus stops, a. o., the cars can avoid additional delays by driving in the left lane.

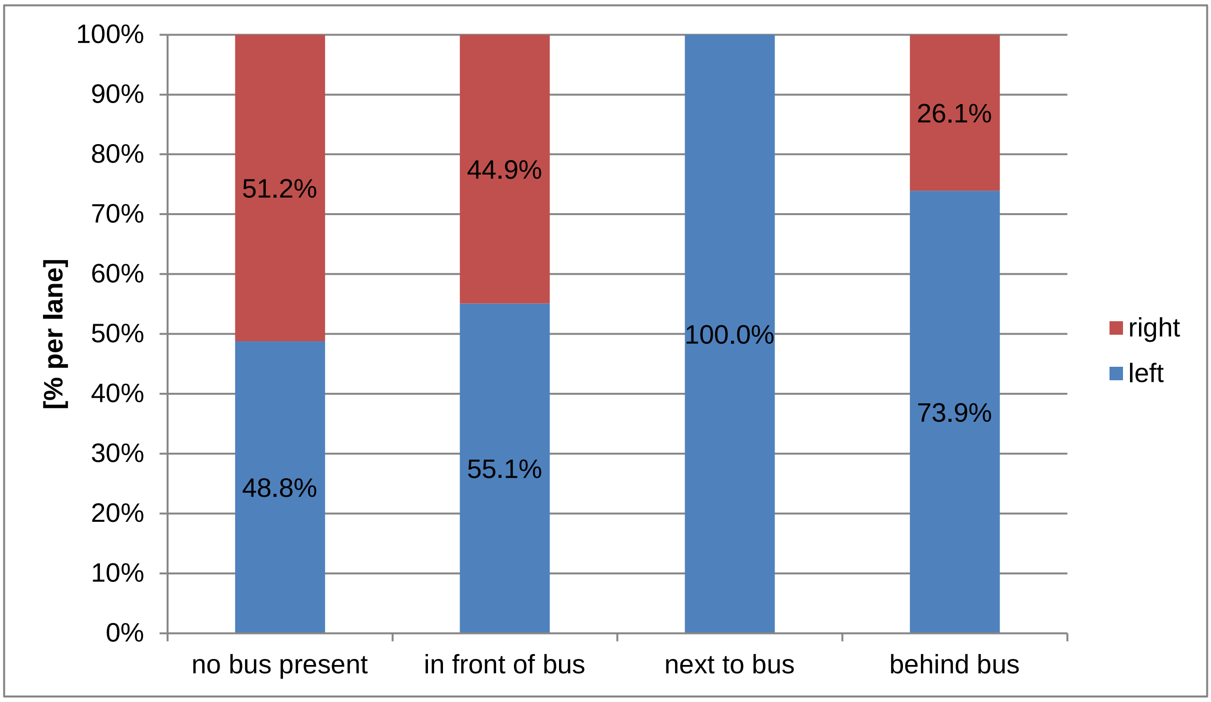

Fig. 9: Lane choice at C2 related to bus position

Fig. 10 confirms the presumption that the distribution of vehicles to the two lanes is better balanced out in times when cars discharge at capacity. When looking at the non-capacity-periods, however, differences between vehicles within and without bus influence can be observed. Whereas drivers who are passing C2 together with a bus avoid the right lane even more than at capacity (only 30.4 % diverge), the right lane is preferred when there is no bus present (52.4%). Several reasons are conceivable: The distance within the right lane is shorter, since there is a right-hand bend, the drivers have to turn right further downstream, or they just feel more comfortable in the right lane. All of these are disabled, when there is a bus; drivers then prefer not to share the lane with public transport.

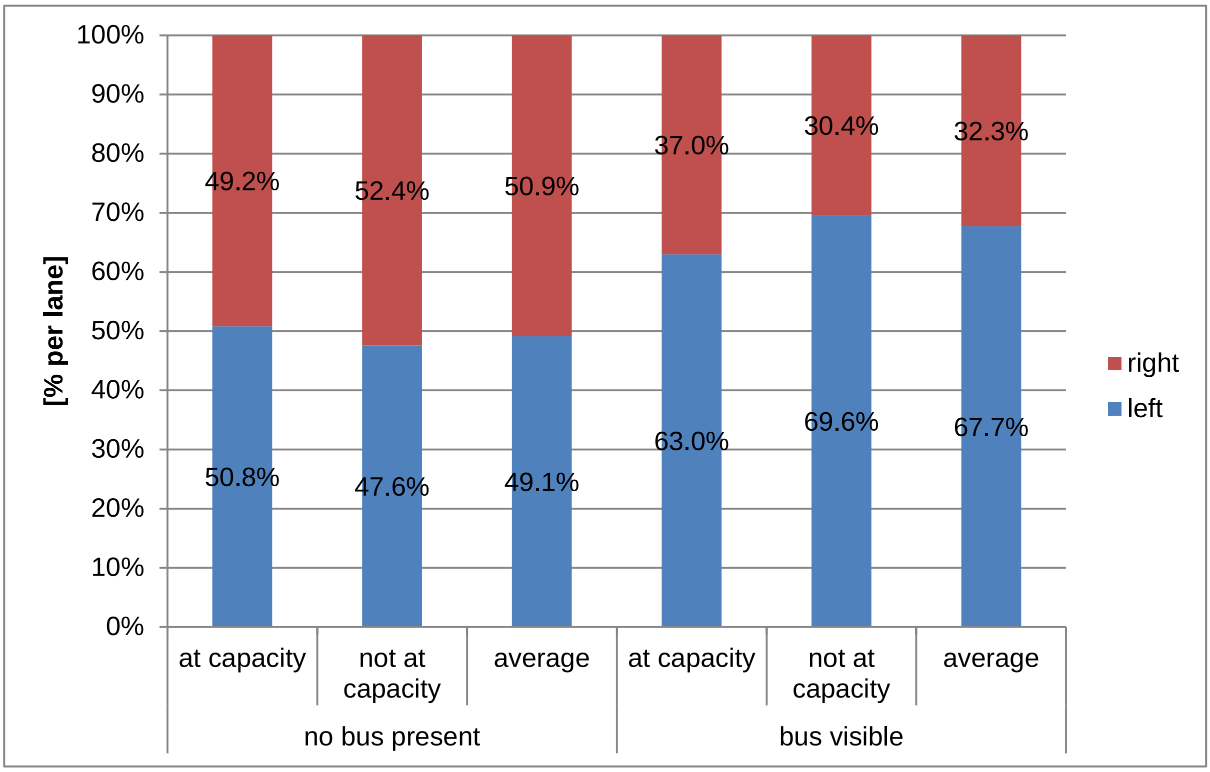

Fig. 10: Lane choice at C2 related to flow state

As discussed before, lane change behavior differs depending on the position of the vehicle relative to the bus. Fig. 11 relates lane choice to both bus position and flow state. It unveils that mainly the vehicles driving behind the bus tend to avoid the right lane, when they do not flow at capacity.

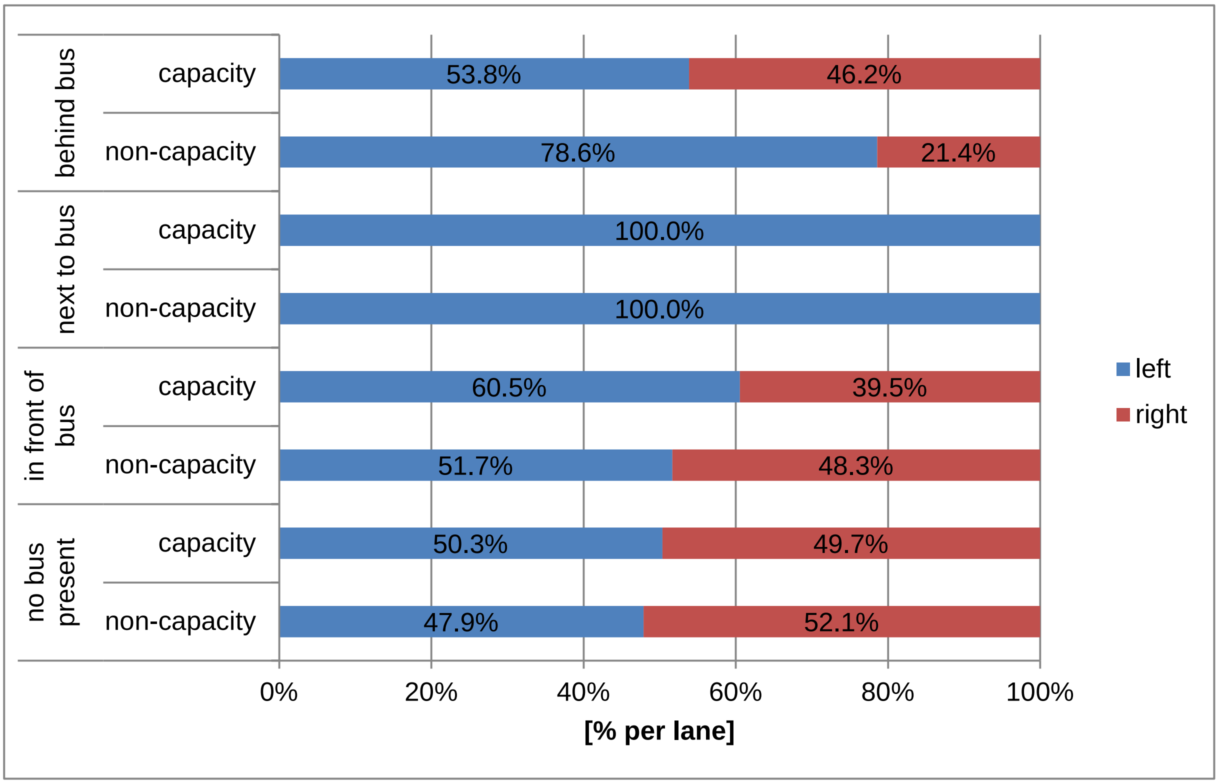

Fig. 11: Lane choice at C2 related to bus position and flow state

6.1.2 Lane choice at location C3

The same analysis as in section 6.1.1 is carried out for location C3. We expect a distribution similar to C2, but there are possibly additional lane changes downstream of C2 that can be monitored at C3.

The comparison of Fig. 12 to Fig. 9 unveils the shift of the lane utilization of cars flowing behind the bus. At C3, the right lane is used much more frequently than at C2 (38.3% vs. 26.1%). One possible explanation is that drivers may realize that the bus is driving at a high speed, so they can diverge to the right lane without any delay. Another possibility is that they are preparing for a right turn further downstream. In this case, the lane change would be independent of the bus.

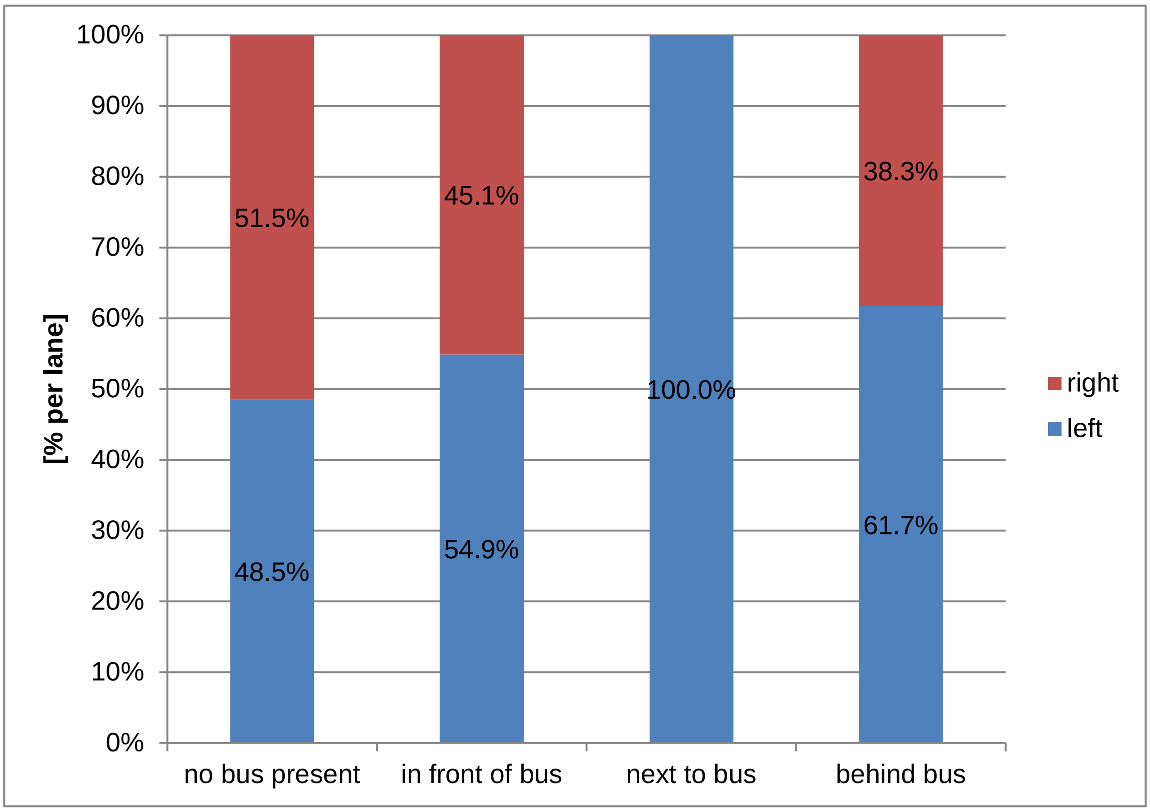

Fig. 12: Lane choice at C3 related to bus position

In Fig. 13, there are fewer differences in the lane choice behavior of vehicles at capacity compared to free flowing vehicles than in Fig. 10. In the absence of a bus, the proportion is reasonably stable at 51.5% in the right lane. Also, under the influence of a bus, the flow state has less effect on the lane choice than at C2.

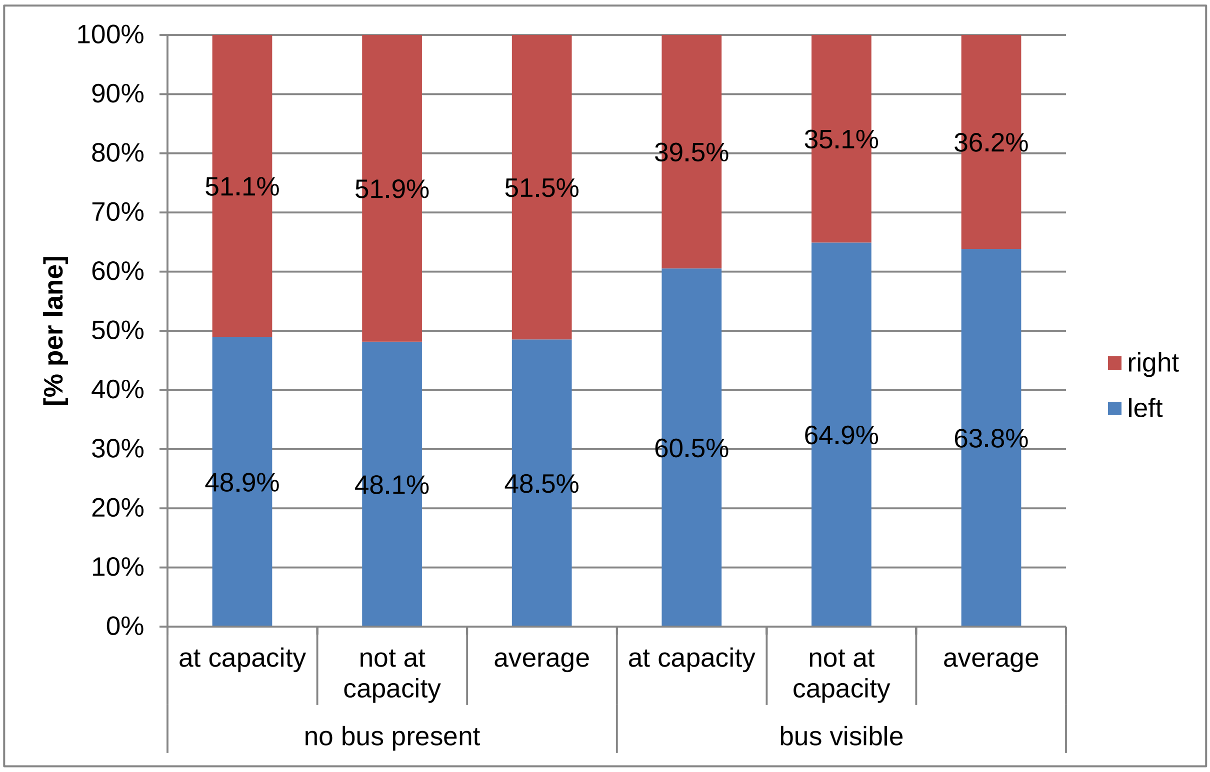

Fig. 13: Lane choice at C3 related to flow state

Fig. 14 shows a quite similar disposition of lane choice as Fig. 10. The only big shift can be stated for the cars flowing behind the bus, but not at capacity. The fraction of vehicles driving in the right lane has increased compared to C2. This effect has already been observed in Fig. 11.

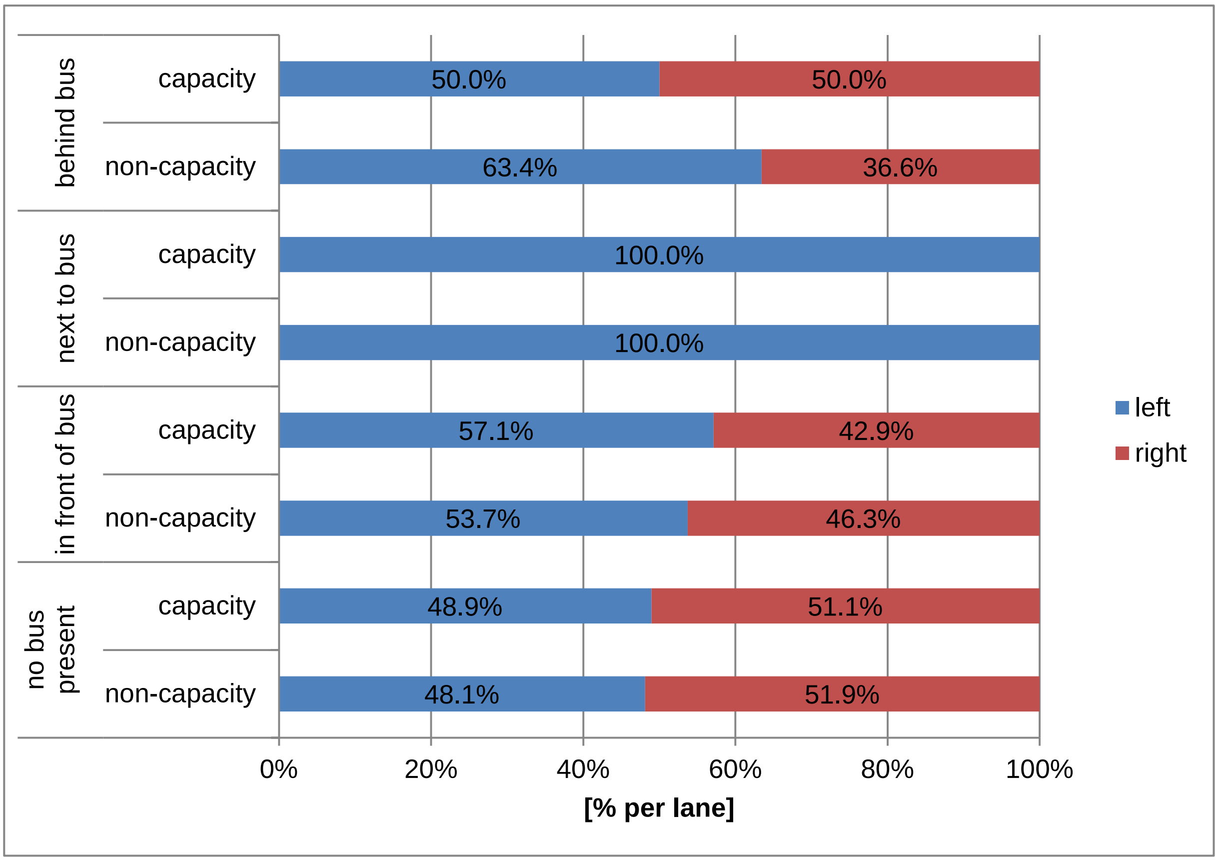

Fig. 14: Lane choice at C3 related to bus position and flow state

6.1.3 Location of lane change

Table 2 presents the comparison of the lane choices at C2 and C3. The red numbers represent the percentage of vehicles which change lane, while the green figures stand for the fractions that stay in the lane chosen at C2. At C2, 514 vehicles out of 1’061 change to the right lane. 75% of them (388 vehicles) stay in the right lane up to C3, whereas 25% change again to the left lane. Exactly the same situation is given for the left lane: 25% (135 vehicles) of all vehicles driving in the left lane at C2 switch to the right lane before they reach C3. Table 2 demonstrates that within the videotaped time segment, 775 lane changes were executed, thereof 66% before C2, right after the bus lane is abolished, and the rest between C2 and C3.

Table 2: Lane change matrix

		lane at C3			
		left		*right*	
lane at C2	[n° of veh]	[n° of veh]	[%]	[n° of veh]	[%]
left	547	412	75%	135	25%
right	514	126	25%	388	75%
total	1061	538	100%	523	100%

6.2 Delays

We are interested in the delays that the presence of a bus causes general traffic.

6.2.1 Delay differences at location C2

As explained in section 5, the flow at C2 is distorted by a traffic light. By just comparing the actual departure times at C2 to the arrival times at C1, huge delays which include waiting times during the red time of the signal will result. In comparison, delays due to the presence of a bus could be minor and hardly detectable. Consequently, the concept of virtual departure times introduced in section 5 was deployed. The analyzed values were named “delay differences” and were calculated by subtracting the virtual departure times from the actual departure times at C2. Several effects influence the delay difference: delays due to a change to the right lane, deceleration on account of the following right-turn, retardation because of congestion, acceleration after the traffic light turns green, and eventually the influence of the bus. It was impossible to quantify each effect separately, but by comparing the delay difference of vehicles influenced by the bus to the ones that do not come into contact with a bus, the impact of a bus’ presence could be examined.

A first overview of the delay deviations is shown in Table 3 and Fig. 15. The histogram is plotted for vehicles within and outside of bus influence. Both seem to follow a normal distribution with means in the interval [1.0; 1.5] and [1.5; 2.0], respectively. Within the data of delay differences outside of bus influence (blue bars in Fig. 15), there is a peak at 0 s. It can be explained by the calculation of the virtual departure curve, which equates the virtual departure time of every first vehicle of a new cycle with its actual departure time.

Table 3: Distribution of delay differences at C2

delay	percentage of vehicles	
interval	*with bus*	*without bus*
[s]	[%]	[%]
[-∞;-2.0]	0.0%	0.2%
[-2.0;-1.5]	0.0%	0.2%
[-1.5;-1.0]	0.5%	1.3%
[-1.0;-0.5]	3.1%	5.6%
[-0.5;0.0]	7.3%	17.5%
[0.0;0.5]	5.7%	13.3%
[0.5;1.0]	13.0%	15.3%
[1.0;1.5]	17.2%	14.8%
[1.5;2.0]	20.3%	11.5%
[2.0;2.5]	12.0%	7.6%
[2.5;3.0]	10.9%	4.7%
[3.0;3.5]	4.7%	4.1%
[3.5;4.0]	3.1%	1.6%
[4.0;4.5]	1.6%	0.8%
[4.5;5.0]	0.5%	0.6%

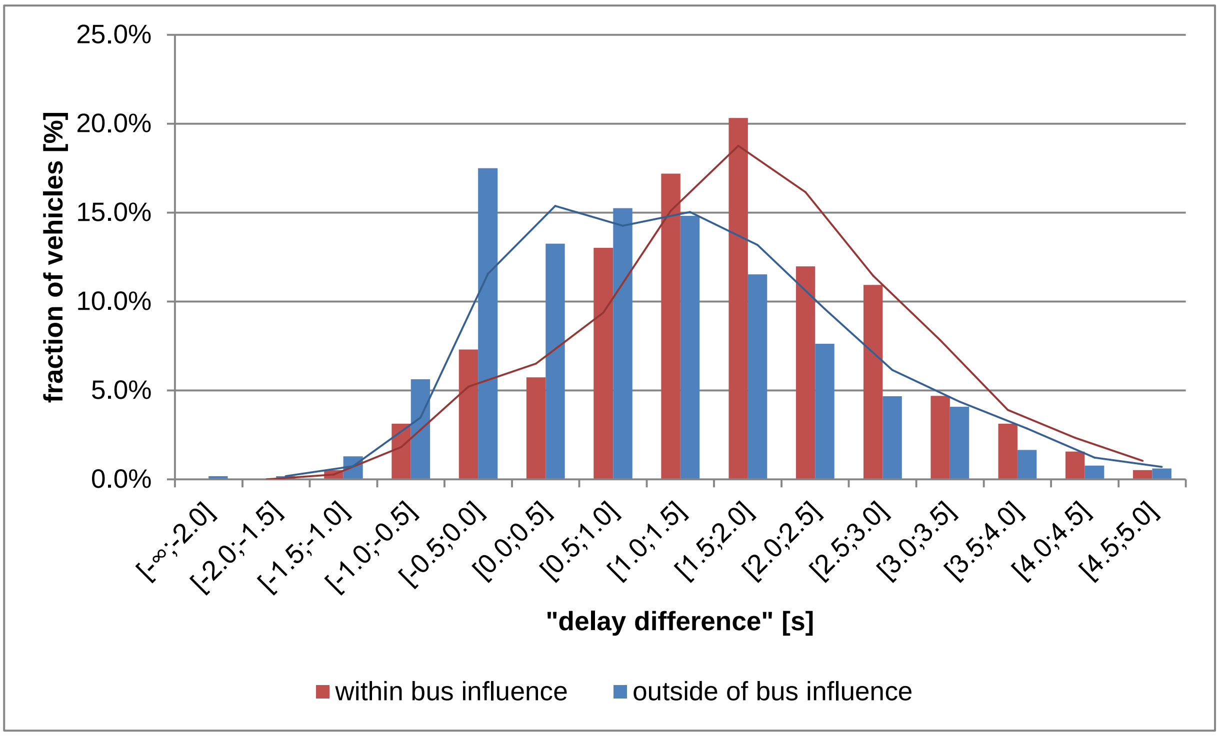

Fig. 15: Histogram of delay differences at C2

The distribution shows that the delay differences are generally higher under the influence of a bus. The values in Table 4 confirm this presumption: The delay differences in the presence of a bus average 1.57 s, which is significantly higher than the delay difference during the absence of a bus (1.05 s). For the statistical tests see appendix A 4, pages A-15 ff. Table 4 further unveils that cars flowing behind the bus experience the largest delays, namely almost double (198%) the amount compared to vehicles outside of bus influence, whereas cars driving ahead of a bus suffer practically no additional delays. To understand the latter observation, one has to keep in mind that vehicles that drive ahead of the bus may pass C2 while the bus is still standing at the bus stop and its impact is minor. At first, the overall resulting delay augmentation may also seem minor, since it is just around 0.5 to 1 s. But one has to keep in mind that these delays occur in the short distance of 42 m between C1 and C2 and are thus caused by a speed reduction of at least 7-12 km/h (if the delay develops over the whole distance) or even more (if the delay occurs on the last meters before C2).

Table 4: Delay differences at C2 related to bus position

	"delay difference"		std. dev.	n° of values
position relative to bus	[s]	[%]	[s]	[s]
outside of bus influence	1.05	100%	1.296	1154
within bus influence	1.57	149%	1.122	192
in front of bus	*1.14*	*109%*	*1.029*	*98*
next to bus	*1.83*	*174%*	*0.798*	*25*
behind bus	*2.07*	*198%*	*1.120*	*69*
all vehicles	1.12	-	1.285	1346

Table 5 further analyzes the influence busses exert on general traffic speed in the road segment where the two modes interact for the first time, i.e. where the dedicated bus lane is abolished. We assume a free-flow travel time of 3 s for the distance between C1 and C2. The average travel time of cars flowing outside of bus influence is set 100%, and the travel times of all other vehicles are calculated relatively. Vehicles driving behind a bus suffer a travel time increase of 25% compared to cars flowing in the absence of a bus, which corresponds to a speed reduction of 20%. The loss of speed of cars passing C2 next to the bus averages 16%. Vehicles driving ahead of the bus, however, encounter only small decreases in velocity.

Table 5: Bus influence on speed between C1 and C2

	delay diff.	travel time C1-C2		speed
position relative to bus	[s]	[s]	[%]	[%]
outside of bus influence	1.05	4.05	100%	100%
within bus influence	1.57	4.57	113%	89%
in front of bus	*1.14*	*4.14*	*102%*	*98%*
next to bus	*1.83*	*4.83*	*119%*	*84%*
behind bus	*2.07*	*5.07*	*125%*	*80%*
all vehicles	1.12	4.12	-	-

Fig. 16 relates the delay difference to the position of the bus and the lane in which the vehicles are driving. The red bars represent the fraction of vehicles flowing in the respective lane. It can be stated that the cars passing C2 in the absence of a bus or ahead of it suffer a slightly bigger delay (+0.2 s/ +0.3 s) in the right lane. The difference is significant at a level of 95% (see statistical test in appendix A 4 on page A-16), which may be due to the lane change itself and to the heavier braking in the inner lane of the right turn. The latter effect should be minor, since the actual right turn begins only a few meters after the C2 line. There is a reciprocal ratio for the delays of vehicles following a bus: Additional delays in the left lane are slightly higher than those in the right lane, but the difference is not statistically significant. The reason why cars in the right lane do not experience more delays than those in the left lane could be the high fraction of vehicles utilizing the left lane, which would result in smaller speeds. Another possibility is that some drivers in the left lane are shy to overtake the bus and hence have to decelerate.

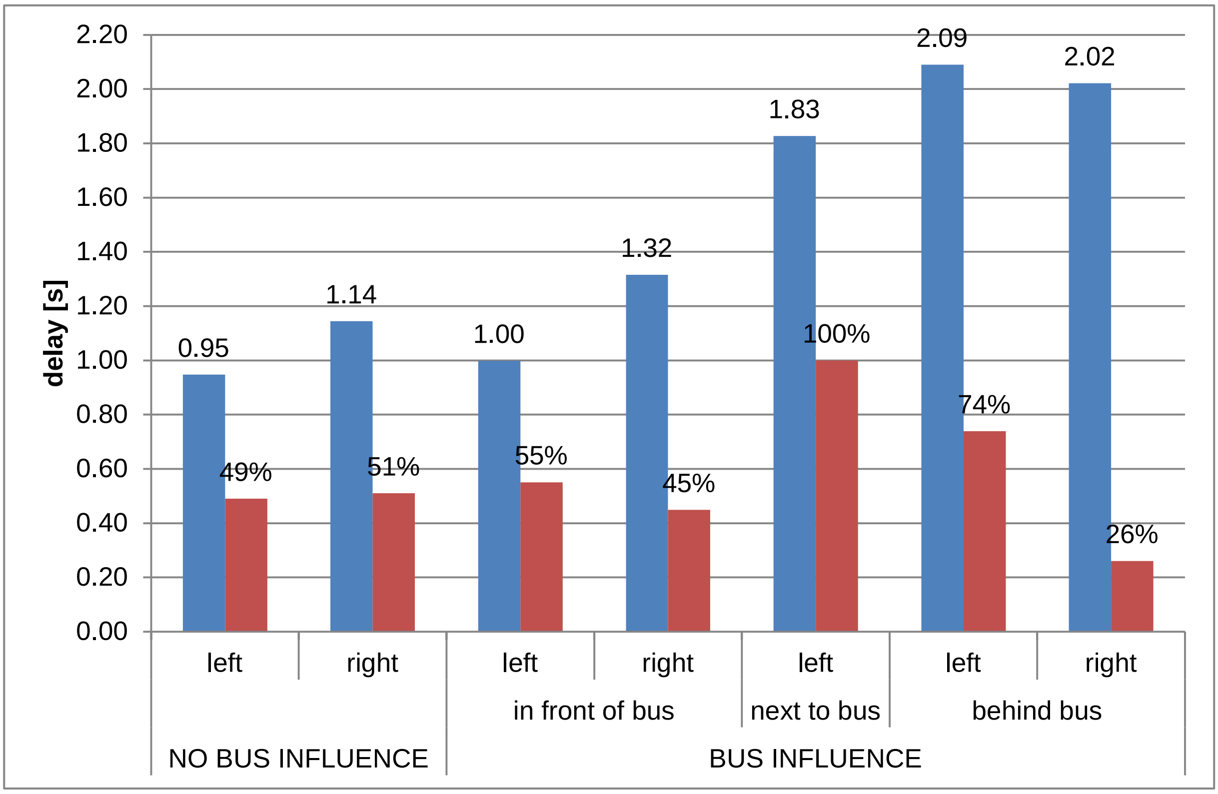

Fig. 16: Delay differences at C2 related to bus position and lane choice

6.2.2 Delays at location C3

The delays at C3 are calculated conventionally, by subtracting the departure time at C2 and the free-flow travel time between C2 and C3 from the departure time at C3. The distance between C2 and C3 measures 60 m. Assuming a free-flow speed of 50 km/h, the free-flow travel time amounts 4.3 s. The vehicles won't flow at 50 km/h on the whole trip between C2 and C3, because they have to decelerate by reason of the right turn. The intensity of braking is hard to quantify though, since it depends on various factors. Therefore, the computed delays include deceleration factors.

Table 6 and Fig. 17 depict a slightly flatter distribution than that of the delay differences at C3. The histogram of the delays under bus influence features a drop in the interval [3.0s; 3.5s], which remains unexplained and may be coincidental. The two curves seem to differ only slightly, which is affirmed by Table 7: The means of the delay distributions without and within bus influence amount 3.57 s and 3.53 s, respectively. The deviation is not statistically significant, as the t-test in appendix A 4 on page A-18 concludes. A significant difference of 15% or about 0.5 s can yet be stated between the averages of delays outside of bus influence and delays of vehicles driving next to a bus.

Table 6: Distribution of delays at C3

delay	**percentage of vehicles**	
interval	*with bus*	*without bus*
[s]	[%]	[%]
[-∞;-2.0]	5.3%	3.5%
[-2.0;-1.5]	9.9%	9.5%
[-1.5;-1.0]	13.8%	13.8%
[-1.0;-0.5]	13.2%	17.7%
[-0.5;0.0]	17.8%	17.9%
[0.0;0.5]	15.1%	16.1%
[0.5;1.0]	13.8%	9.2%
[1.0;1.5]	4.6%	5.5%
[1.5;2.0]	1.3%	2.8%
[2.0;2.5]	0.7%	0.4%
[2.5;3.0]	0.0%	0.3%
[3.0;3.5]	0.7%	0.0%
[3.5;4.0]	0.0%	0.0%
[4.0;4.5]	0.0%	0.0%
[4.5;5.0]	0.0%	0.0%

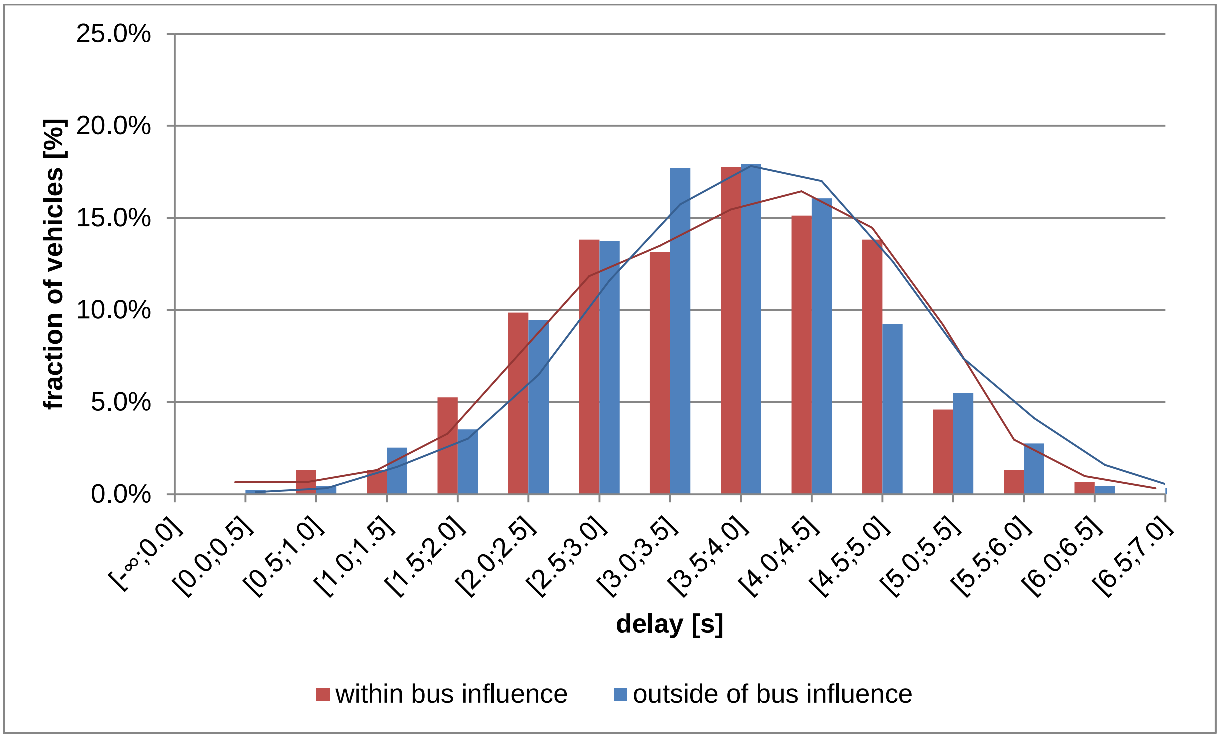

Fig. 17: Histogram of delays at C3

Table 7: Delays at C3 related to bus position

position relative to bus	delay [s]	delay [%]	std. dev. [s]	n° of values [-]
outside of bus influence	3.57	100%	1.070	1101
within bus influence	3.53	99%	1.203	171
in front of bus	*3.25*	*91%*	*1.098*	*90*
next to bus	*4.09*	*115%*	*1.741*	*30*
behind bus	*3.74*	*105%*	*0.915*	*51*
all vehicles	3.56	-	1.090	1272

In Table 8, the change of velocity due to bus presence is listed. Compared to the road section between C1 and C2, the speed reduction between C2 and C3 is minor. Vehicles driving next to the bus suffer the largest loss of speed (-6%), whereas cars flowing ahead of a bus go even faster than those outside of bus influence (+4%).

Table 8: Bus influence on speed between C2 and C3

position relative to bus	delay diff. [s]	travel time C2-C3 [s]	travel time C2-C3 [%]	speed [%]
outside of bus influence	3.57	7.87	100%	100%
within bus influence	3.53	7.83	100%	100%
in front of bus	*3.25*	*7.55*	*96%*	*104%*
next to bus	*4.09*	*8.39*	*107%*	*94%*
behind bus	*3.74*	*8.04*	*102%*	*98%*
all vehicles	3.56	7.86	-	-

The analysis of Fig. 18 unveils a different ratio of delays than at C2 (compare Fig. 16): At C3, delays in the left lane are slightly higher than in the right lane. Since 25% of the cars in either lane carry out a lane change between C2 and C3, as described in section 6.1.3, the lane change share of the delays at C3 should be similar in both lanes. The delays in the absence of a bus are almost equal in both lanes (3.61 s and 3.53 s). The difference of 0.08 s can be explained by the longer arc of the right-hand bend in the left lane. The delays of cars driving in front of the bus in the same lane exhibit the smallest delays. A possible explanation of this phenomenon is that the drivers want to be sure not to block the bus further downstream and therefore go faster. The vehicles behind the bus also experience more delays in the left lane, at C3 as well as at C2 (compare Fig. 16). The reason could be the higher utilization of the left lane.

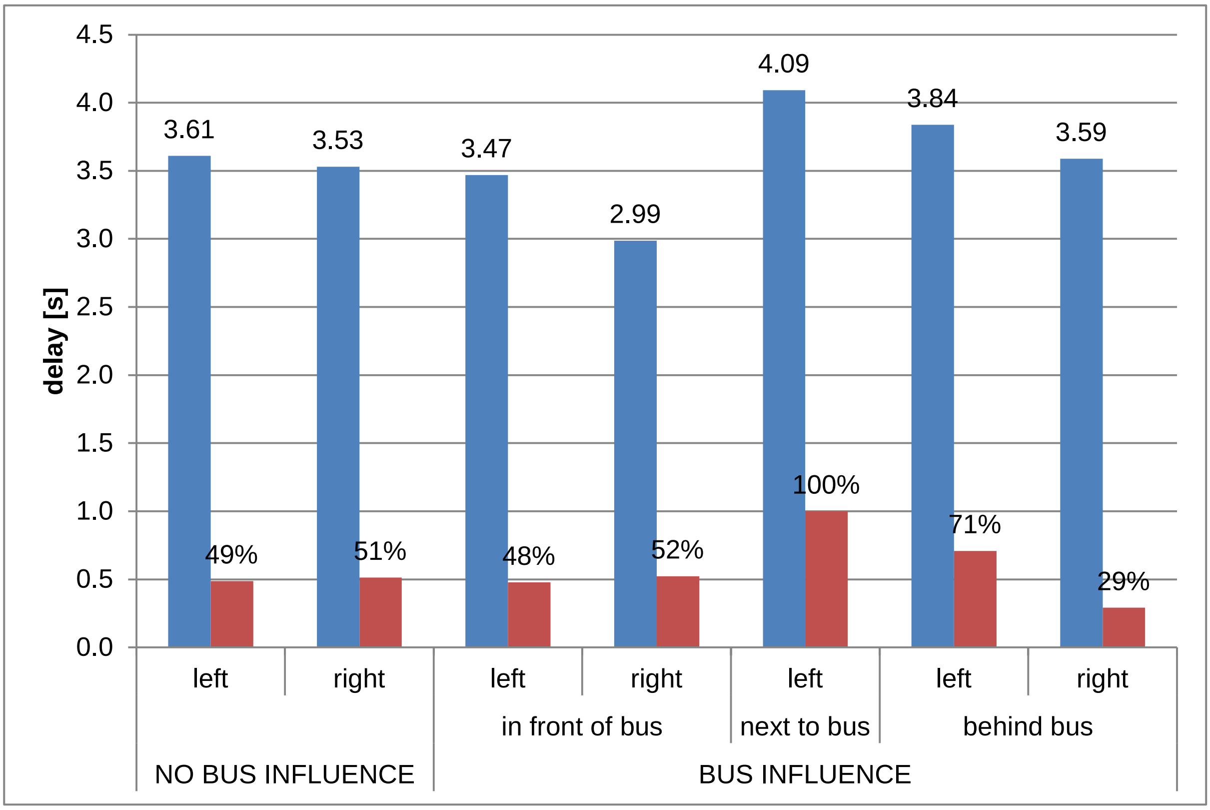

Fig. 18: Delays at C3 related to bus position and lane choice

As discussed before, the delay consists of several factors. At C3, the effect of the speed-up after the traffic light turns green goes into the delay values. Vehicles that pass C2 at the very beginning of a cycle lose much time, because they have to accelerate from standstill. Fig. 19 illustrates this issue very well. The delays of vehicles driving at capacity are generally higher than those of vehicles at free flow, which is due to the acceleration time and possibly to the higher flow as well. Here, the designation “free flow” is used for the traffic state that does not correspond with “capacity” as defined in section 5, knowing that “free flow” is not the opposite of “capacity”, and the term is therefore not precise. Vehicles driving next to a bus suffer more delays at free flow than at capacity, but on account of the small sample size, the difference is not significant.

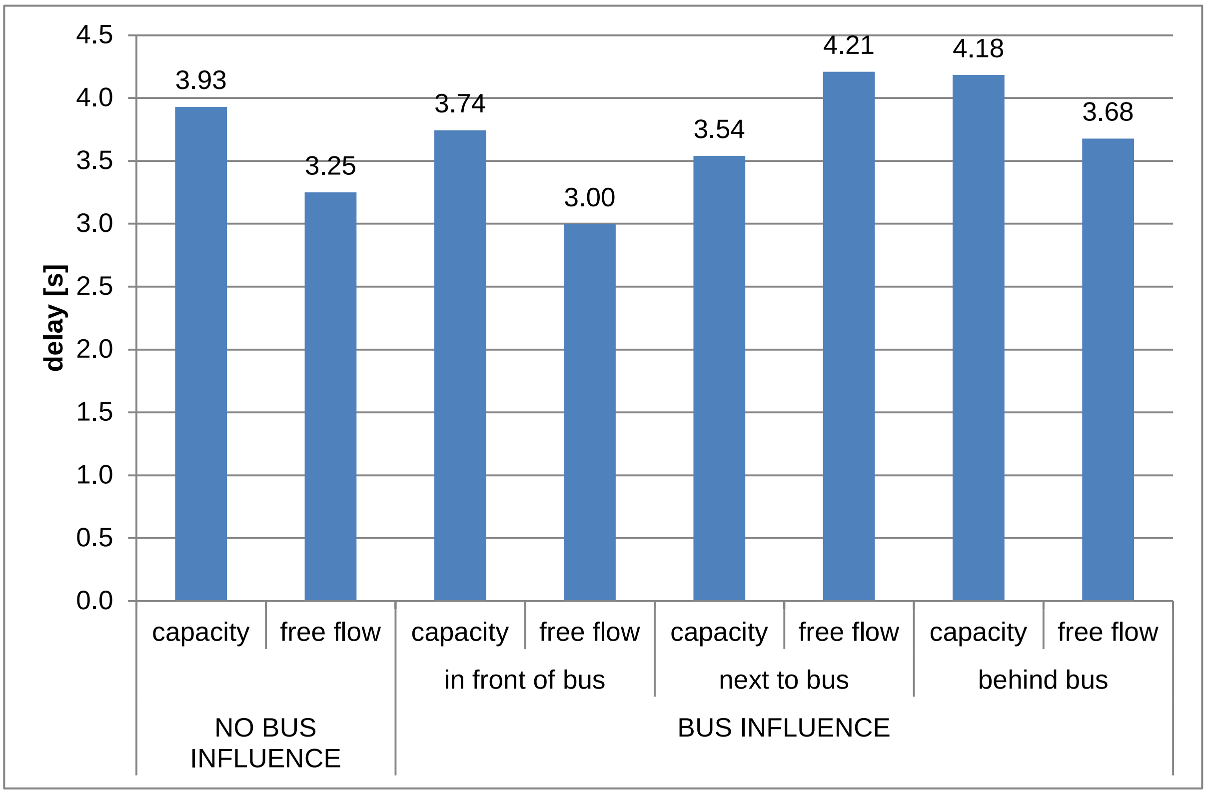

Fig. 19: Delays at C3 related to bus position and flow state

6.2.3 Total delay

To gain a comprehensive insight into the delays at Winzerhalde, the "delay differences" at C2 and the delays at C3 were added. Table 9 lists the total delays related to the bus position at C3. Vehicles driving ahead of a bus practically don't encounter more delays than those flowing in the absence of a bus. The delays of cars flowing next to or behind a bus, however, are 29% to 30% higher. Assuming a free flow travel time of 102 m divided by 50 km/h equal 7.3 s for the entire distance between C1 and C3, the travel time of cars flowing behind a bus is 11-12% higher than that of cars outside of bus influence. Their speed is thus reduced by approximately 10% on the distance between C1 and C3, as Table 10 indicates. From sections 6.2.1 and 6.2.2 we know that the lion's share of the reduction in velocity falls upon the road section between C1 and C2, where the bus lane is abolished.

Table 9: Total delay related to bus position at C3

position relative to bus C3	total delay [s]	total delay [%]	std. dev. [s]	n° of values [-]
outside of bus influence	4.54	100%	1.365	1101
within bus influence	5.18	114%	1.487	171
in front of bus	*4.57*	*101%*	*1.202*	*90*
next to bus	*5.87*	*129%*	*1.606*	*30*
behind bus	*5.92*	*130%*	*1.422*	*51*
all vehicles	4.64	-	1.400	1272

Table 10: Speed change related to bus position at C3

position relative to bus C3	total delay [s]	total travel time [s]	total travel time [%]	speed [%]
outside of bus influence	4.54	11.84	100%	100%
within bus influence	5.18	12.48	105%	95%
in front of bus	*4.57*	*11.87*	*100%*	*100%*
next to bus	*5.87*	*13.17*	*111%*	*90%*
behind bus	*5.92*	*13.22*	*112%*	*90%*
all vehicles	4.64	11.94	-	-

6.3 Capacity

A particularly interesting analysis is the impact of a bus' presence on traffic flow. It holds several difficulties due to the setting of Winzerhalde: At C1, the vehicles arrive more or less randomly distributed, since the last traffic light is quite far upstream. However, at C2, the random distribution is disrupted by the traffic signal. There, cars discharge at capacity at the beginning of every new cycle. In this section, we will look at vehicles flowing at capacity only, because capacity is independent of the cars' random arrival times. We can thereby better examine flow shifts due to present buses. However, the results found in this section are not necessarily valid only for capacity, but could well be applied to flows in general.

As explained, only vehicles driving at capacity (according to the definition in section 5) were considered for the analysis. The flow was calculated by summing up all vehicles of one capacity period and dividing the resulting number by the lapse of time between the last and the first vehicle. For this analysis, it was important that the buses were included in the data as passing vehicles. Had they been left out of the calculation, there would have been gaps in the departure curve, and the flow would consequently have been underestimated.

Flow is often measured in vehicle equivalents to take into account different vehicle lengths. Trucks, for example, would equate 2 or 3 vehicle equivalents, because they are longer than cars. In order to simplify the data extraction, this refinement was omitted, so that flow would be slightly underestimated.

6.3.1 Capacity at C1

At C1, the concept of capacity introduced in section 5 could not be applied, because there was no camera upstream of C1. As explained, cars arrive at C1 more or less randomly distributed. Since demand during the morning peak is high, however, there are well periods when cars arrive at a very high rate. To evaluate capacity at C1, a method a little less sophisticated than at C2 and C3 had to be employed: We assumed that in phases of capacity, vehicles would pass C1 with headways of less than 2.5 s.[2] Applying this condition, we were able to determine capacity flows at C1, and capacities were derived of all flows that compromised more than 4 vehicles. As a result, we received an average capacity of 2'370 veh/h at C1. The capacities were calculated separately for all vehicles passing the bus during its halt at the bus stop. The resulting capacity is no smaller than when there is no bus present. We can thus conclude that

[2] If the headway benchmark is chosen smaller (e.g. 2.0 s), almost no contiguous flows of more than 4 vehicles can be made out.

buses driving in their own reserved lane do not exert any influence on cars. Given this insensitivity, we assume 2’370 veh/h to be the general C1 capacity.

Table 11: Capacity at C1

	flow mean	std. dev.	n° of values
	[veh/h]	[veh/h]	[-]
no bus present	2371	329.0	50
within bus influence	2340	261.6	10
all vehicles	2365	317.0	60

6.3.2 Capacity at location C2

The calculated capacity flows at C2 were each complemented manually by information about the bus position. For the last vehicle of every capacity flow (which is decisive), we verified whether it flowed behind, next to, or ahead of a bus. The information about bus position had to be handled with care, though: Each flow consisted of several vehicles driving at different positions related to the bus, so most flows could not be assigned to one distinct bus position. We therefore distinguished only two categories: capacity flows preceding a bus and those mainly composed of cars following a bus (including vehicles driving next to it).

The capacity averages 4’090 vehicles per hour when there is no bus present. The value is slightly smaller (3’760 veh/h) when a bus flows behind. However, the flow difference (compared to the case when there is no bus) is not statistically significant (see t-test on page A-23).

In contrast, vehicles driving at capacity behind a bus flow at a significantly lower rate of 2’610 veh/h, which is 36 % less than in the absence of a bus. It can thus be assumed that the bus reduces capacity of the road behind it.

Table 12: Capacity at C2 related to bus position

	flow mean		std. dev.	n° of values
bus position	[veh/h]	[%]	[veh/h]	[-]
no bus present	3326	100%	423.0	56
bus behind capacity flow	-	-	-	0
bus within capacity flow	3181	96%	334.4	5
bus in front of capacity flow	2611	79%	232.9	3

6.3.3 Capacity at location C3

The same analysis already made at C2 was now carried out for C3. Due to some downstream congestion that had to be omitted, the data for C3 is slightly less extensive than for C2. Since the bus position can change between C2 and C3 (as most cars drive faster than the bus), the number of values for each bus position is different from C2.

Table 13 presents the result of the capacity analysis at C3: The average flow at C3 is not significantly higher or lower than at C2 (see t-test appendix A 4 on page A-26). This can be assessed as proof that the algorithm presented in section 5 indeed computes the vehicles driving at capacity.

As observed at C2, capacity is reduced when a bus is succeeding. At C3 the reduction amounts 17%, which is still not statistically significant.

When the bus drives ahead, capacity is reduced by about 33% to 2’640 veh/h. The average capacity flow next to and behind a bus (2’640 veh/h) coincides with the result for C2 (2’610 veh/h) and is significantly lower than the flow in the absence of a bus. The bus thus reduces capacity on the behind road segment by about 36% at C2 and 33% at C3.

It is important to note that there are not so many values describing capacities affected by buses, so their statistical significance is possibly not given.

Table 13: Capacity at C3 related to bus position

	flow mean		std. dev.	n° of values
bus position	[veh/h]	[%]	[veh/h]	[-]
no bus present	3406	100%	481.5	42
bus behind capacity flow	3626	106%	-	1
bus within capacity flow	2819	83%	635.6	3
bus in front of capacity flow	2563	75%	184.0	2

6.3.4 Comparison of capacities at C1, C2, and C3

Not only lane changes, but also the presence of a bus has a great influence on capacity, as Table 14 shows. When there is a bus driving ahead of a capacity flow, capacity is increased by only 8-10% compared to C1. Of course, this can be due to the uneven lane occupation behind a bus (see section 6.1). Generally, capacity augmentation compared to C1 amounts to only 28-38% within bus influence, instead of 67-73% when there is no bus present.

The most interesting finding of this section is the unexpectedly small capacity increase between C1 and C3. Even though the number of accessible lanes is doubled, capacity is raised by only about 70%. There seems to be a significant smoothing effect at C1, whereas at C2 and C3, lane changes absorb quite a large ratio of the capacity augmentation.

Table 14: Comparison of capacities

	capacity at C1		**capacity at C2**		**capacity at C3**	
bus position	[veh/h]	[%]	[veh/h]	[%] of cap_{C1}	[veh/h]	[%] of cap_{C1}
no bus present	2371	100%	4090	173%	3963	167%
within bus influence	2371	100%	3268	138%	3025	128%
bus behind capacity flow	*2371*	*100%*	*3760*	*159%*	*3280*	*138%*
bus within capacity flow	*2371*	*100%*	*2611*	*110%*	*2643*	*111%*

6.4 Non-capacity flow

In section 6.3, we examined only capacity to eliminate the flow-determining issue of random arrivals. A sufficient road capacity is important especially during the peak hours. However, we are also interested in flows below capacity, to assess the benefits of dynamic bus lanes in times when demand is low.

We therefore considered non-capacity flows (according to the definition in section 5) only. As the arrivals at C1 are random and the headways vary quite a lot, calculating the flows conventionally ($f\left[\frac{veh}{s}\right] = {}^{n}/_{\Delta t}$) would not deliver meaningful results. Another strategy had to be chosen: The comparison of time headways. First, the headways of all vehicles at C1, C2, and C3 were assessed. Thanks to the very accurate data extraction, the headway shift between C1 and the two downstream locations were calculated individually for every car. If the headways h are reduced, the flow is increased according to the formula $f[\frac{veh}{s}] = {}^{1}/_{h}$. The absolute values of flow are not of grand interest, because they depend mainly on the arrival rate at C1. More significant are the flow or headway changes. Nevertheless, a histogram of all measured headways at C1 was plotted to give an overview of the arrival rate (Fig. 21). The distribution seems to comply with a Gaussian bell curve at first sight, but there are many outliers on the high side which typify the random arrivals. Fig. 21 further includes some vehicles with very small headways even under 1 s. Since such low headways are hardly practicable in one single lane, as we have it at C1, the values could originate from measuring inaccuracies. There is a more probable explanation, however: A few cars change to the bus lane before C1, even though it is officially not accessible to general traffic at this location. Since these cars could not be left out of the analysis in order not to distort delays at C2 and C3, there are situations where two cars pass C1at almost the same time, but in two lanes instead of one. For the analysis of headways and flows, all headways smaller than 1 s were omitted.

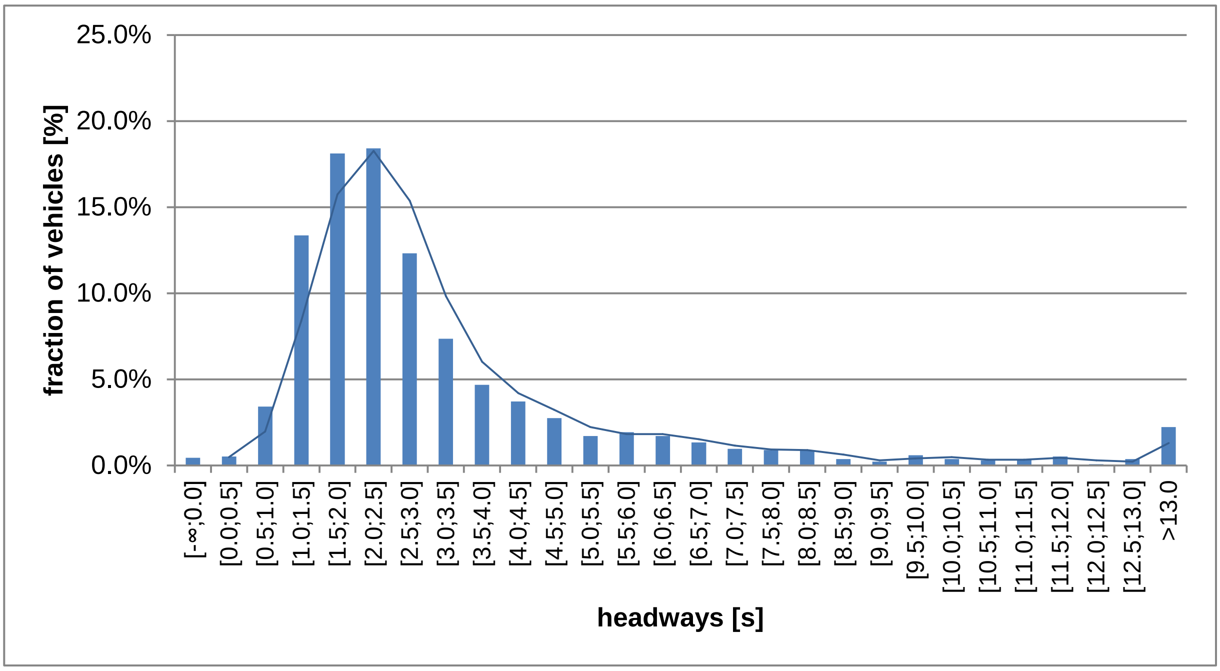

Fig. 20: Histogram of headways at C1

The significance of the following results was tested by means of t-tests for dependent samples, since flow shifts are a matter of one sample that is measured twice. The t-tests can be checked in appendix A-A 5 on p. A-29 ff.

6.4.1 Non-capacity flow shift between C1 and C2

Table 15 depicts a listing of the measured headways at C2 and C3. Note that the standard deviations are very high due to the flat frequency distribution of headways shown in Fig. 21. First, the means of headways at C1 (h_{C1}) and C2 (h_{C2}) are calculated, and h_{C2} is expressed as fraction of h_{C1}. According to $f[\frac{veh}{s}] = {}^{1}/_{h}$, the inverse of h_{C2}/h_{C1} is the flow at C2 related to C1. The last column of Table 15 now unveils that non-capacity flows increase by about 3.5% due to the abolition of the dedicated bus lane. The shifts in flow hardly differ, depending on the bus position – apart from the vehicles driving behind the bus, which experience only a small flow increase. In contrast, the vehicles driving ahead of the bus flow at a 5.5% higher rate than at C1.

Table 15: Non-capacity flow shift between C1 and C2

	headway C1 (h_{C1})		headway C2 (h_{C2})			n° of values	flow at C2	flow shift
	mean	*std. dev.*	*mean*	*std. dev.*	h_{C2}/h_{C1}	*n*	$1/(h_{C2}/h_{C1})$	$f_{C2}-f_{C1}$
bus position at C2	[s/veh]	[s/veh]	[s/veh]	[s/veh]	[%] of h_{C1}	[-]	[%] of f_{C1}	[%] of f_{C1}
no bus present	3.01	2.739	2.91	2.810	97%	495	103.5%	3.5%
in front of bus	3.44	3.300	3.26	3.313	95%	56	105.5%	5.5%
next to bus	2.83	1.111	2.74	1.331	97%	11	103.1%	3.1%
behind bus	2.87	2.951	2.83	2.963	99%	53	101.4%	1.4%
all vehicles	3.03	2.791	2.93	2.850	97%	615	103.5%	3.5%

6.4.2 Non-capacity flow shift between C1 and C3

The flow increases by about 5.0% between C1 and C3, as Table 16 indicates. At C3, the flow of vehicles driving next to the bus is much lower (-8.6%) than at C1. Of course, these cars only have one lane at their disposal, but this is the same at C1. As already stated in section 6.2.2, vehicles driving next to the bus suffer much more delays. They seem to avoid overtaking the bus, while following vehicles don't succeed to the bus level. The result is a decreased flow.

Vehicles ahead of the bus pass C3 at a significantly higher rate, which can also be observed at C2. These differences coincide with the findings of section 6.2.2 that delays are small ahead of a bus and high when driving next to it. Table 16 further implies that flows are higher at C3 than at C2, which could be due to the raised speed limit after C3 or to the traffic light and the right-hand bend at C2.

Table 16: Non-capacity flow shift between C1 and C3

bus position at C3	headway C1 (h_{C1})		headway C3 (h_{C3})			n° of values	flow at C3	flow shift
	mean	*std. dev.*	*mean*	*std. dev.*	h_{C3}/h_{C1}	*n*	$1/(h_{C3}/h_{C1})$	$f_{C3}-f_{C1}$
	[s/veh]	[s/veh]	[s/veh]	[s/veh]	[%] of h_{C1}	[-]	[%] of $flow_{C1}$	[%] of f_{C1}
no bus present	3.08	3.035	2.92	3.190	95%	358	105.5%	5.5%
in front of bus	2.99	1.970	2.81	1.751	94%	37	106.5%	6.5%
next to bus	3.21	2.954	3.51	3.411	109%	14	91.4%	-8.6%
behind bus	2.30	1.433	2.21	1.733	96%	35	104.0%	4.0%
all vehicles	3.02	2.863	2.88	3.011	95%	444	105.0%	5.0%

Flow shifts related to the headway at C1 are of interest, because they could give indications about how much flow increases depending on demand. However, headways at C1 are not to be equated with demand, because they are measured by vehicle, whereas demand should be determined over a longer period. Consequently, there is no trend to be detected in Fig. 21. Apart from the very small C1 headways between 0 and 2 s (which increase until C3), the flow shifts are mainly negative, but with no noticeable subjection to headways at C1.

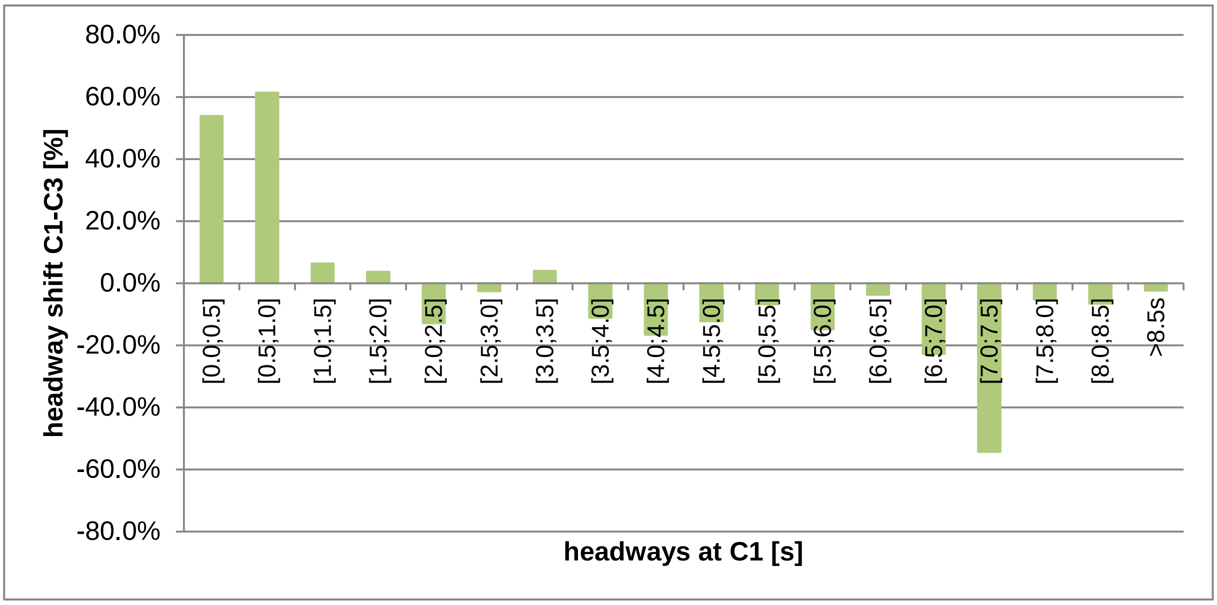

Fig. 21: Flow shifts h_{C1}-h_{C3} sorted by headways at C1

7 Conclusions and Future Prospects

The results found in section 6 are now to be applied to the concept of dynamic bus lanes in Zurich. One predication can be made without even considering the numeric results: As discovered in section 4.1.2, drivers in Zurich prefer not to use lanes which are later converted to dedicated bus lanes. They want to avoid enforced lane changes, which could possibly become due at inconvenient moments. This behavior has been observed both in very congested systems such as Hardbrücke and in zones and periods of less demand, at Frankentalstrasse, for example. Therefore, a BLIP system, introduced by Eichler and Daganzo (2006), which forces vehicles out of the lane when a bus is approaching, is unthinkable in the city of Zurich. BLIP systems are unpredictable for the drivers, so that lane changes would have to be executed at unknown points in time as well as unknown locations. As a consequence, the dynamic bus lanes would scarcely be used and practically serve as dedicated bus lanes.

In contrast, IBL systems are thoroughly imaginable in Zurich. Under the condition that they will not have to leave the lane later, drivers would in all probability use the bus lane voluntarily, as is the case at Winzerhalde. In an IBL system, as opposed to Winzerhalde, cars do not have to interact with public transport buses, which could even increase the drivers' sense of security.

Assuming a dynamic bus lane (DBL) at Winzerhalde instead of the existing setting, some considerations have to be made:

- Vehicles outside of bus influence would exhibit the same behavior as before: The longitudinal lights in the pavement would be off when there is no bus visible, and cars would flow as always.
- In DBL systems, there are two categories of cars driving ahead of the bus: the vehicles in the same lane as the bus, which changed to that lane before the lights started flashing, and the vehicles driving just ahead of the bus, but in the other lane.
- The lead of vehicles driving ahead of the bus in the same lane will be much larger, since one aim of a dynamic bus lane is to clear the road before the bus arrives. However, the drivers will be advised of the approaching bus by signalization, so that some of the behavior described in section 6 might be observed in IBL systems as well: Vehicles ahead of the bus drive faster, with less delays and higher flows than vehicles outside of bus influence.
- Vehicles driving closely ahead of the bus will have to use the remaining lanes, since the bus lane is closed. Their behavior will thus more likely resemble the observed be-

havior of cars flowing next to the bus. However, since the two lanes are separated, the capacity of a single lane next to a dedicated bus lane calculated in section 6.3.1 could be reached.

- The findings for cars driving next to the bus will apply to dynamic bus lanes as well. However, it is possible that drivers feel more secure due to the actual demarcation of the bus lane separating the two modes and thus drive faster and with shorter headways.
- Cars driving behind the bus in DBL systems will exhibit similar behavior as observed at Winzerhalde, which results in large delays and decreased capacity. It is even possible that the DBL is less frequently used behind a bus, because it is misunderstood as a dedicated bus lane or because drivers, intimidated by the signalization, are shy to profit from it. Since more vehicles concentrate in one lane then, delays would increase as discovered in sections 6.2.1 and 6.2.2.

The above list states that in DBL systems, there will be fewer vehicles driving in two lanes in front of the bus, but more vehicles driving in the left lane next to or ahead of it. This would naturally affect capacity: If there is only one lane accessible, capacities won’t be higher than at C1. Hence, the overall capacity of a DBL system at Winzerhalde will be smaller than it is now, because the smoothing effect is not strong enough to compensate the lane reduction in times of bus passings. From a car’s point of view, the existing setting downstream of Winzerhalde is preferable to a DBL.

Like upstream of Winzerhalde, there are many dedicated bus lanes in Zurich. The results of this work indicate that at these locations a DBL would ameliorate the flow conditions of cars: All capacities measured at C2 and C3 are higher than at C1, where we currently have a dedicated bus lane. Let’s also look at the fraction of time during which vehicles are affected by buses: About 20 buses per hour pass by Winzerhalde, which is a medium frequency. Looking at the data, we count 190 vehicles influenced by a bus and 1’170 vehicles that pass C2 when there is no bus present. Therefore, only about 14% of all counted vehicles suffer delays caused by the bus during the morning peak, and capacity is reduced only during approximately 14% of the time, whereas it is still higher than in a lane next to a dedicated bus lane. In a DBL instead of mixed road use, this percentage would certainly be a bit higher, because the influence of the bus reaches further downstream. Also, the flow reductions would be greater, since the right lane would be closed ahead of the bus. Still, capacity would not fall under that of a lane next to a dedicated bus lane at any time. One can thus reasonably assume that even with much higher bus rates, cars would benefit from a dynamic bus lane.

There is one problem that has to be mentioned in the context of mixed road use as well as dynamic bus lanes: bus stops. In times of high demand, vehicles flowing after a bus will encounter delays if they have to wait behind the bus stop and derogate road capacity as they change to the other lane like in an ordinary merging situation. In order to prevent this, it is conceivable to implement DBLs mainly in road sections where there are no bus stops. In an intra-urban environment, these are rare, though. Another possibility is to design the DBL not to unblock the road space behind the bus until the bus leaves the stop. In all probability, however, bus stops will only cause major delays when demand is at capacity and above. As section 6.1revealed, cars driving below capacity do not diverge behind the bus immediately after the bus lane is released. If the driver knows the location or has the bus stop within his range of vision, he will stay in the left lane until he has overtaken the bus. If this is the case, capacity corresponds with that of a dedicated bus lane. In order to obtain certitude in the issue of bus stops, experiments could be carried out in mixed road use systems with more than one lane. According to the level of demand, delays and loss of flow due to bus stops could be determined.

The analysis of Winzerhalde served to evaluate the actual benefit of dynamic bus lanes for cars in Zurich. In future research, high-demand locations in the city are to be tested for their DBL-suitability. Basically, all existing dedicated bus lanes come into consideration. Possible restrictions such as high bus frequencies have to be taken into account to avoid disproportions between the benefit of cars and the disturbance of public transport. When it comes to implementation, a concrete DBL arrangement including signalization, monitoring, and control has to be developed to meet Zurich’s needs.

The work at hand exclusively treats the effects of buses on cars. To gain a comprehensive understanding of the interactions between cars and buses, the analysis has to be carried out from the public transport point of view as well. Only then can the use of dynamic bus lanes be estimated in a holistic manner.

8 Literature

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Viegas, J. and B. Lu (2001) Widening the scope for bus priority with intermittent bus lanes. Transportation Planning and Technology, 24(2), 87-110.

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Appendix

A 1 Possible Investigation Sites for Situation A

Bahnhof Hardbrücke

Bus lines: 33 and 72

Fig. 22 shows the satellite picture of the southern part of the bridge, just south of the bus stop Bahnhof Hardbrücke (see Fig. 22).

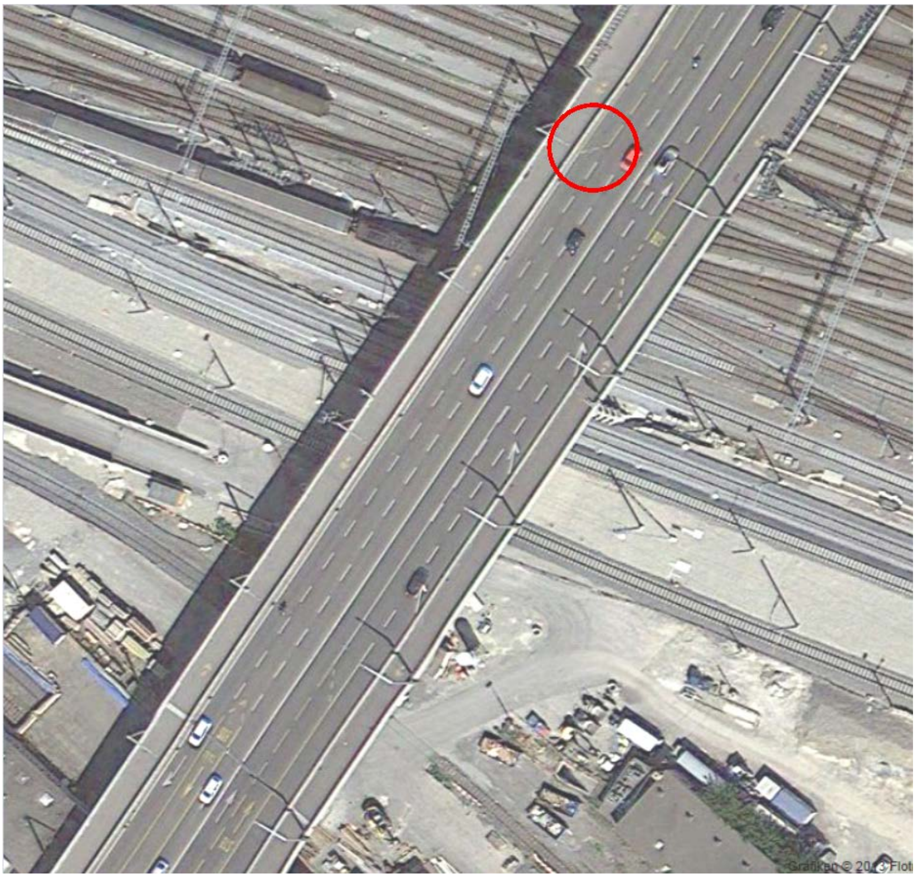

Fig. 22: Situation A south of Bahnhof Hardbrücke [Source: Google Earth]

The north-south direction is considered. The bus is first conducted in its own lane, while two separate lanes are at the general traffic's disposal. Then, at the location of the red circle in Fig. 22, the dedicated bus lane ends and becomes accessible to all vehicles. The bus then moves to the middle lane, which becomes a bus-only lane further downstream. The rightmost lane is later dedicated to right-turning vehicles. Thus, the fraction of vehicles that diverge voluntarily to the outer lane after the abolishment of the dedicated bus lane can possibly not be observed properly, since the lane change is due to a shift in direction.

A site inspection reveals another reason why this location cannot be used for the analysis: Nearly all drivers refuse to utilize the middle lane. They seem to know that the middle lane is closed to general traffic further downstream, so they either stay in the leftmost lane or change directly to the right-turning lane. Even if the queue in the right-turning lane reaches the bus lane, the middle lane is not chosen, but vehicles arrange in the queue and change to the right-most lane as soon as possible (i.e., when the bus lane ends). Thus, the abolishment of the dedicated bus lane does not actually add a lane for the use of general traffic.

Hardbrücke, above Escher-Wyss-Platz

Bus lines: 33 and 72

The setting of Fig. 23 is located directly above Escher-Wyss-Platz. In the south-north direction, the outer bus lane becomes a shared lane. From the beginning of the shared section, this rightmost lane is dedicated to right-turning vehicles; so again, the number of voluntary lane changes cannot be measured.

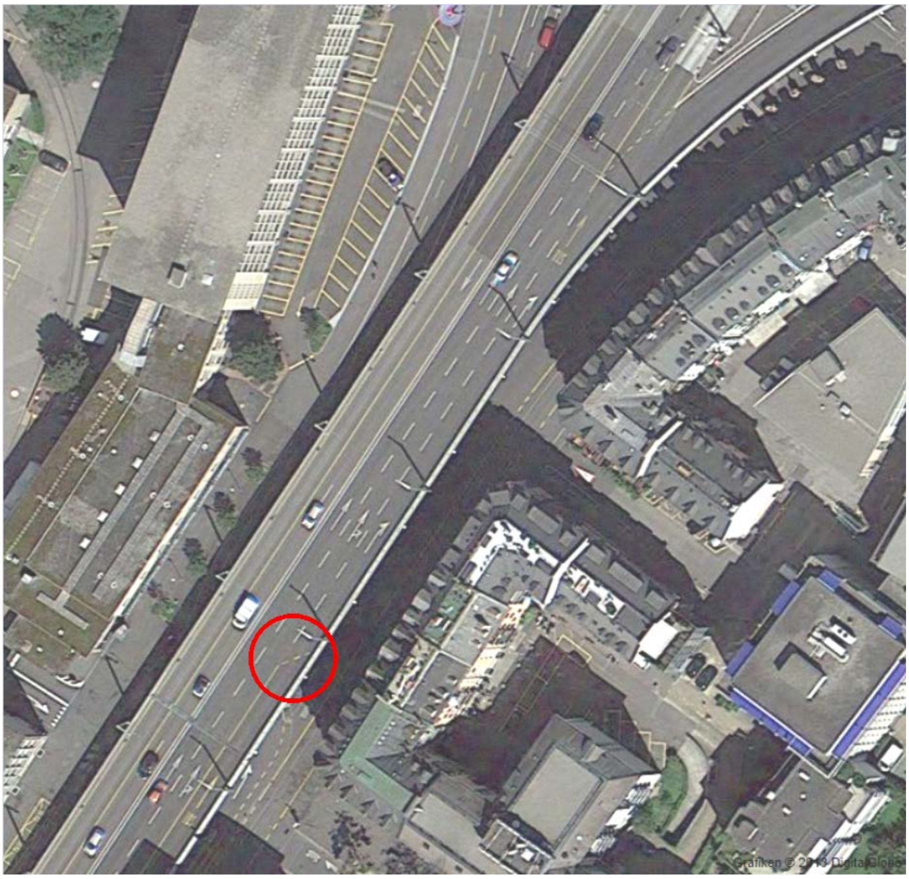

Fig. 23: Situation A above Escher-Wyss-Platz [Source: Google Earth]

Manessestrasse/Staffelstrasse

Bus line: 33

In the north-south direction of Manessestrasse, the leftmost lane is a dedicated bus lane made accessible for cars after the signalized intersection at Staffelstrasse (see Fig. 24). The lane can then be utilized by left-turning vehicles. Voluntary lane changes cannot be measured. In addition, there is the problem that buses are prioritized at the signal and thus never interact with general traffic.

Fig. 24: Situation A at intersection Manessestrasse/Staffelstrasse [Source: Google Earth]

Schaffhauserstrasse/Glattalstrasse

Bus lines: 29, 75, 742, 768

The two northern arms of the intersection in Fig. 25 both feature the same setting: The rightmost bus lane is open to right-turning vehicles. The streets in the respective directions are expected to be congested mainly in the morning, because they link two different highway exits to the city. On Glattalstrasse, which is the west arm, there is a large queue in the left-turning lane during the morning peak, while the right lane is barely used. Delays would be difficult to observe here. The north arm, Schaffhauserstrasse, is generally much less charged. Vehicles can drive at free-flow speed.

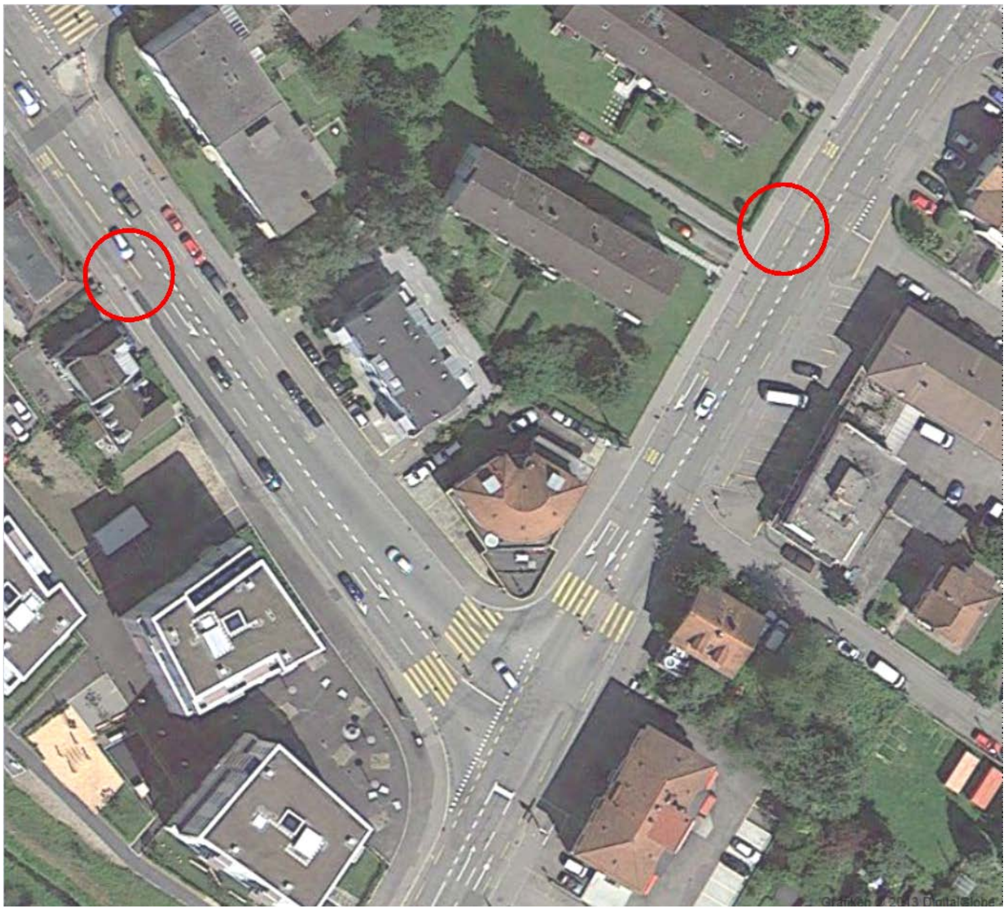

Fig. 25: Situation A at Glattalstrasse/Schaffhauserstrasse [Source: Google Earth]

Birmensdorferstrasse

Bus lines: 215, 220, 235, 245

The street section of Fig. 26 is located at Birmensdorferstrasse on the way from the city hospital Triemli to Uitikon. A very long bus-only lane is made accessible for vehicles which have to turn right at the next intersection. The location is not an ideal investigation site, because voluntary lane changes cannot be measured.

Fig. 26: Situation A at Birmensdorferstrasse direction Uitikon [Source: Google Earth]

Mythenquai

Bus lines: 161, 165

At Mythenquai, right before the intersection with General-Guisan-Quai, there is a setting very similar to the one at Winzerhalde (see section 4.1.1). The very right bus lane, which is covered by trees in Fig. 27, is open to right-turning traffic going to Bürkliplatz. There is another right-turning lane right next to it and a traffic signal. Mythenquai is a less suitable investigation site than Winzerhalde, as it features a very low bus frequency of only 4 buses per hour.

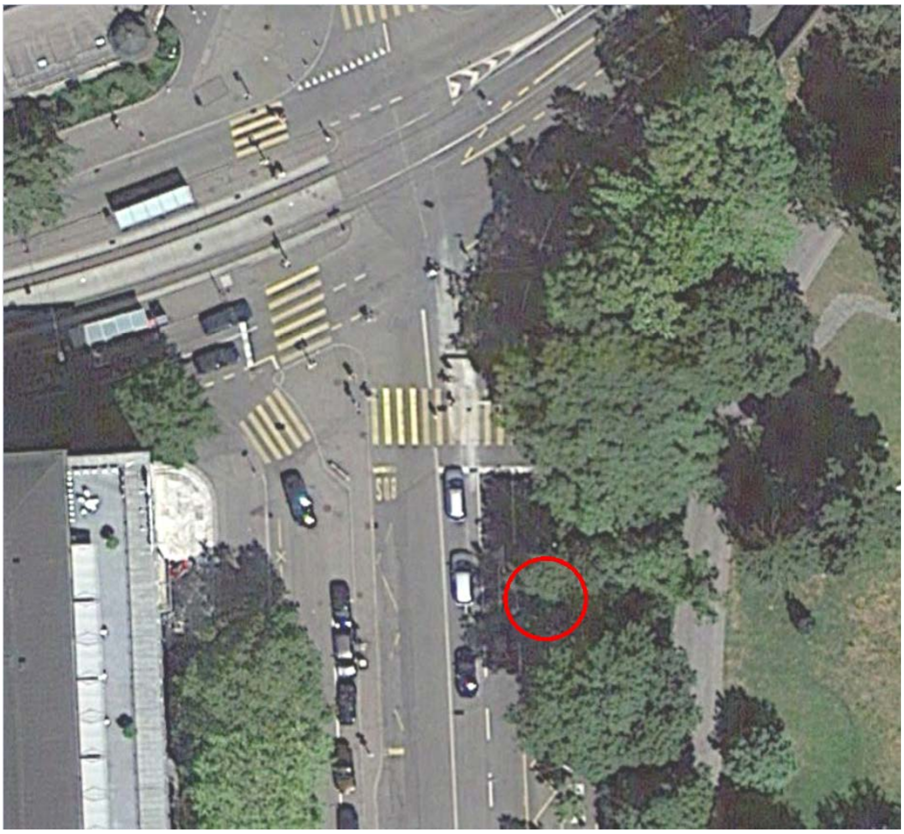

Fig. 27: Situation A at Mythenquai direction Bürkliplatz [Source: Google Earth]

A 2 Possible Investigation Sites for Situation B

Winzerhalde

Bus lines: 80, 89, 304, 308

Opposite the investigated bus stop Winzerhalde, in the east-west direction, there is a setting where the buses stop in the very right lane, and other vehicles are forced to merge (see Fig. 28). As long as there is no bus present, it is a normal merging situation, but when the bus is approaching, the setting can be compared to a BLIP situation. Unfortunately, the intersection is controlled by a signal light, and the vehicles from the east arm going straight as well as the bus from Europabrücke going west do not run in the same phases; there are thus no interactions to be observed.

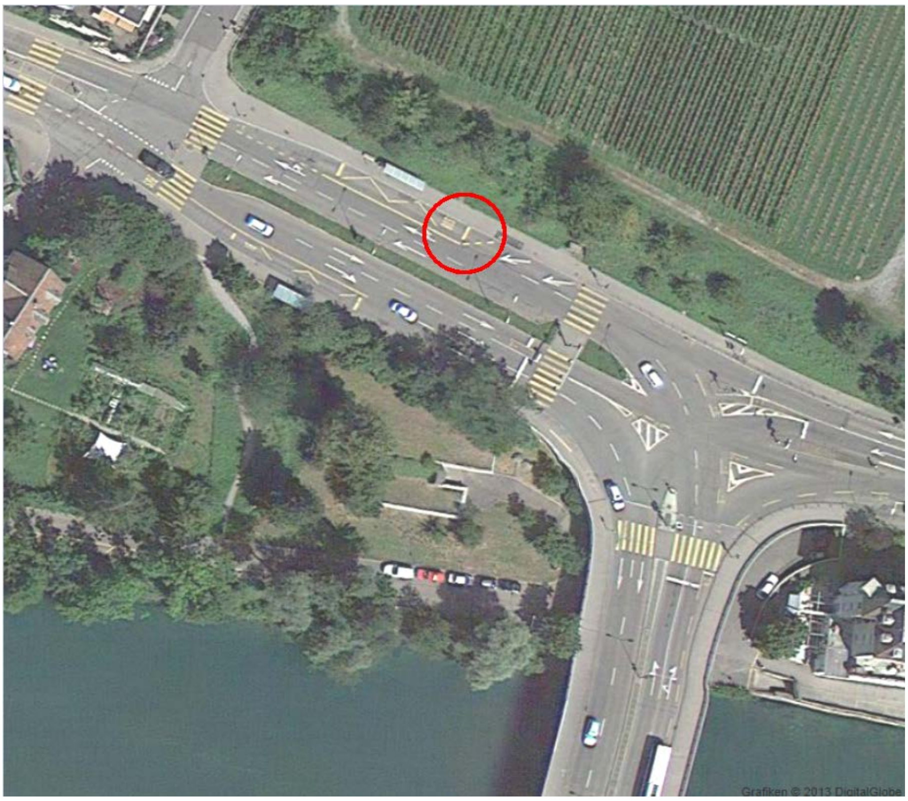

Fig. 28: Situation B at bus stop Winzerhalde [Source: Google Earth]

Frankentalstrasse

Bus lines: 89, 485

At Frankentalstrasse, north of the junction Frankental, the right lane is converted into a bus lane, so vehicles have to merge to the remaining lane (see Fig. 29). One downside of this location is the relatively low frequency of buses (8 per hour). A visual inspection during the evening peak hour revealed that the very right lane is mainly used by drivers who want to turn right into the small residential street. The cars that follow the street eastwards change to the left lane far before they are actually forced to, in order to avoid lane changes at the last moment, when they might inconvenience other vehicles. Therefore, the effects of situation B) can hardly be investigated at Frankentalstrasse.

Fig. 29: Situation A at Frankentalstrasse [Source: Google Earth]

Hardbrücke

Bus lines: 33, 72

Setting B can be found at Hardbrücke, south of the bus stop Bahnhof Hardbrücke, in the north-south direction (see Fig. 30). The red circle in Fig. 30 shows the conversion of the middle lane into a dedicated bus lane. Upstream, there are three shared lanes. The rightmost lane is reserved for right-turning vehicles.

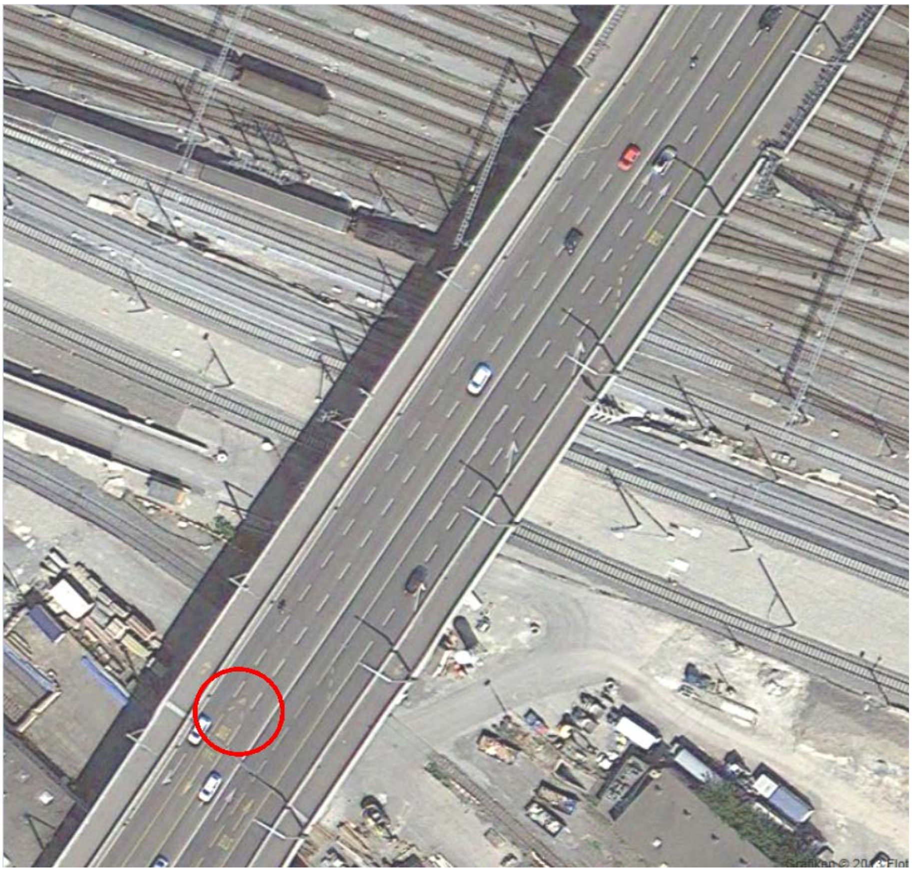

Fig. 30: Situation B south of Bahnhof Hardbrücke [Source: Google Earth]

The two settings A and B on the southern part of Hardbrücke are very near to each other with a distance of only 100 m in between, which makes it difficult to allocate the observed effects to one single event.

Unfortunately, a visual inspection in the evening peak hour uncovered that the middle lane is practically not used by cars. The drivers seem to know that it is converted into a bus-only lane, so they prefer not to travel in it at all and avoid additional lane changes. Given this driving behavior, the expected effects cannot be observed at the location Bahnhof Hardbrücke.

A 3 Timetables Bus Stop Winzerhalde

Source: Verkehrsbetriebe Zürich (http://www.vbz.ch), timetable 2013

Line 80

80

Partner im ZVV
ZVV-App für iPhone/Android
ZVV-Contact
0848 988 988

Winzerhalde

Richtung Triemlispital

Gültig ab 09.12.2012

Ungefähre Reisezeit in Minuten

Bahnhof Oerlikon Nord
Max-Bill-Platz
Birchstrasse
Chaletweg
Mötteliweg
Glaubtenstrasse
Schumacherweg
Lerchenhalde
ETH Hönggerberg
Hönggerberg
Meierhofplatz
Zwielplatz
Wartau
Winzerstrasse
Winzerstrasse Süd

Hohenklingensteig
Winzerhalde
1 Tüffenwies
4 Bahnhof Altstetten
5 Bristenstrasse
7 Lindenplatz
9 Rautistrasse
10 Untermoosstrasse
11 Albisriederdörfli
12 Albisrieden
13 Goldackerweg
14 In der Ey
16 Triemli
17 Triemlispital

Als Sonntage gelten auch: 25. und 26. Dezember, 1. und 2. Januar, Karfreitag, Ostermontag, 1. Mai, Auffahrt, Pfingstmontag, 1. August

h	Montag-Freitag	Samstag	Sonn- und Feiertag	h
5	10_c 25_c 40_c 48_c 55_c	10_c 25_c 40 55	55	5
6	03 10 17 25 32 40 45 51 57	10 25 40 55	10 25 40 55	6
7	04 11 18 24 31 37 43 49 55	10 25 40 53	10 25 40 55	7
8	01 07 13 20 27 33 40 47 51 58	03 13 23 33 43 53	10 25 40 55	8
9	04 11 18 25 33 40 47 53	03 13 23 30 38 45 53	10 25 40 55	9
10	00 07 15 22 30 37 45 52	00 08 15 22 30 37 45 52	10 23 33 43 53	10
11-14	00 07 15 22 30 37 45 52	00 07 15 22 30 37 45 52	03 13 23 33 43 53	11-14
15	00 07 15 22 30 37 44 51 58	00 07 15 22 30 37 45 52	03 13 23 33 43 53	15
16	05 12 18 24 31 37 44 51 58	00 07 15 22 30 37 45 52	03 13 23 33 43 53	16
17	04 11 18 24 31 38 44 51 58	00 07 15 22 30 37 45 52	03 13 23 33 43 53	17
18	05 11 18 25 31 39 46 52	00 07 15 21 29 37 45 53	03 13 23 33 43 53	18
19	00 07 15 22 30 37 45 52	00 08 15 23 30 38 45 53	03 13 23 33 43 53	19
20	00 07 15 21 29 39_c 49_c 59_c	00 10 19 29 39_c 49_c 59_c	03 13 21 30_c 39_c 49_c 59_c	20
21	09_c 19_c 29_c 39_c 49_c 59_c	09_c 19_c 29_c 39_c 49_c 59_c	09_c 19_c 29_c 39_c 49_c 59_c	21
22	09_c 19_c 29_c 39^c_b 40^c_a 49^c_b 55^c_a 59^c_b	09_c 19_c 29_c 39_c 49_c 59_c	09_c 19_c 29_c 40_c 55_c	22
23	09^c_b 10^c_a 19^c_b 25^c_a 29^c_b 39^c_b 40^c_a 49^c_b 55^c_a 59^c_b	09_c 19_c 29_c 39_c 49_c 59_c	10_c 25_c 40_c 55_c	23
0	10_c 25_c 40_c	10_c 25_c 40_c	10_c 25_c 40_c	0

a Montag - Donnerstag   b Nur Freitag   c bis Triemli

Nach besonderem Fahrplan verkehren die Kurse am 24. und 31. Dezember, am Sechseläuten, am Züri-Fascht, an der Streetparade und am Knabenschiessen.

Datum: 26.09.2013 18:20:38; Linie: 3-80-A-1-H; Haltestelle: 2904

Line 89

89

Partner im ZVV
ZVV-App für iPhone/Android
ZVV-Contact
0848 988 988

Winzerhalde

Richtung Sihlcity

Gültig ab 09.12.2012

Ungefähre Reisezeit in Minuten

	Holzenholz
	Geeringstrasse
	Friedhofstrasse
	Frankental
	Winzerstrasse Süd
	Hohenklingensteig
▶	Winzerhalde
1	Tüffenwies
4	Bahnhof Altstetten
5	Bristenstrasse
6	Baslerstrasse
8	Letzipark West
9	Kappeli
10	Flurstrasse
11	Albisrank
13	Hubertus
14	Im Gut
16	Schaufelbergerstrasse
17	Schweighof
18	Friesenbergstrasse
20	Im Hagacker
20	Heglanwandweg
22	Strassenverkehrsamt
23	Uetlihof
24	Laubegg
25	Saalsporthalle
26	Sihlcity

Als Sonntage gelten auch: 25. und 26. Dezember, 1. und 2. Januar, Karfreitag, Ostermontag, 1. Mai, Auffahrt, Pfingstmontag, 1. August

h	Montag-Freitag	Samstag	Sonn- und Feiertag	h
5	56	56		5
6	11 26 40 55	11 26 41 56		6
7	10 25 40 55	11 26 41 56		7
8	10 25 41 56	11 26 41 56		8
9	11 26 41 56	11 26 41 56		9
10	11 26 41 56	11 26 41 56		10
11	11 26 41 56	11 26 41 56		11
12	11 26 41 56	11 26 41 56		12
13	11 26 41 56	11 26 41 56		13
14	11 26 41 56	11 26 41 56		14
15	11 26 41 56	11 26 41 56		15
16	10 25 40 55	11 26 41 56		16
17	10 25 40 55	11 26 41 56		17
18	10 25 41 56	11 26 41 55		18
19	11 26 41 56	10 25 40 55		19
20	10 25 40 55	10 25 40 55		20
21				21
22				22
23				23
0				0

Nach besonderem Fahrplan verkehren die Kurse am 24. und 31. Dezember, am Sechseläuten, am Züri-Fäscht, an der Streetparade und am Knabenschiessen.

Datum: 26.09.2013 10:22:50; Linie: 3-89-A-1-H; Haltestelle: 2934

Line 304

304

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Winzerhalde

Richtung
Zürich, Bahnhof Altstetten N

Gültig ab 09.12.2012

Ungefähre Reisezeit in Minuten

- Dietikon, Bahnhof
- Fahrweid, Limmatbrücke
- - Au
- - Brunaustrasse
- Geroldswil, Grindlen
- - Dorfstrasse
- - Zentrum
- - Dorfstrasse
- - Weibrig
- Weiningen ZH, Schulhaus
- - Lindenplatz
- - Ausserdorf
- Unterengstringen, Aegelsee
- - Sennenbüel
- - Langacher
- Oberengstringen, Paradies
- - Zentrum
- - Lanzrain
- - Eggbühl
- Zürich, Frankental
- - Winzerstrasse Süd
- - Hohenklingensteig
- **Zürich, Winzerhalde**
- 1 - Tüffenwies
- 3 - Bahnhof Altstetten Nord

Als Sonntage gelten auch: 25. und 26. Dezember, 1. und 2. Januar, Karfreitag, Ostermontag, 1. Mai, Auffahrt, Pfingstmontag, 1. August

h	Montag - Freitag	Samstag	Sonn- und Feiertag	h
5	47	47	47	5
6	19 48	17 44	17 44	6
7	18 48	14 45	14 44	7
8	18 48	15 45	14 44	8
9	16 46	15 46	14 44	9
10	16 46	16 46	14 44	10
11	16 46	16 46	14 44	11
12	16 46	16 46	14 44	12
13	16 46	16 46	14 44	13
14	16 46	16 46	14 44	14
15	16 46	16 46	14 44	15
16	16 48	16 46	14 44	16
17	18 48	16 46	14 44	17
18	18 48	16 46	14 44	18
19	16 46	16 44	14 44	19
20	16 44	14 44	14 44	20
21	14 44	14 44	14 44	21
22	14 44	14 44	14 44	22
23	14 44	14 44	14 44	23
0	14 44	14 44	14 44	0

Datum: 26.09.2013 10:12:31; Linie: 7-304-A-1-H; Haltestelle: 2304

Line 308

308

ZVV-App für iPhone/Android
ZVV-Contact
0848 988 988

Winzerhalde

Richtung
Zürich, Bahnhof Altstetten N

Gültig ab 09.12.2012

Ungefähre Reisezeit in Minuten

Urdorf, Oberurdorf
- Sonne
- Spitzacker
- Neumatt
- Niederurdorf
- Schlierenstrasse
- Feldegg

Schlieren, Spital Limmattal
- Heimeliweg
- Nassacker
- Brunngasse
- Bahnhof
- Feldstrasse
- Talacker-Windegg

Unterengstringen, Langwisen
- Eckstein
- Sennenbüel Nord
- Sennenbüel
- Langacher

Oberengstringen, Paradies
- Zentrum
- Lanzrain
- Eggbühl

Zürich, Frankental
- Winzerstrasse Süd
- Hohenklingensteig

▶ **Zürich, Winzerhalde**
1 - **Tüffenwies**
3 - **Bahnhof Altstetten Nord**

Als Sonntage gelten auch: 25. und 26. Dezember, 1. und 2. Januar, Karfreitag, Ostermontag, 1. Mai, Auffahrt, Pfingstmontag, 1. August

h	Montag-Freitag	Samstag	Sonn- und Feiertag	h
5	32	32	32	5
6	02 33	02 30	02 30	6
7	03 33	00 31	00 30	7
8	03 33	01 31	00 30	8
9	01 31	01 31	00 30	9
10	01 31	01 31	00 31	10
11	01 31	01 31	01 31	11
12	01 31	01 31	01 31	12
13	01 31	01 31	01 31	13
14	01 31	01 31	01 31	14
15	01 31	01 31	01 31	15
16	01 33	01 31	01 31	16
17	03 33	01 31	01 31	17
18	03 33	01 31	01 31	18
19	01 31	01 29	01 30	19
20	01 30	00 30	00 30	20
21	00 30	00 30	00 30	21
22	00 30	00 30	00 30	22
23	00 30	00 30	00 30	23
0	00 30	00 30	00 30	0

Datum: 26.09.2013 10:15:59; Linie: 7-308-A-1-R; Haltestelle: 2604

A 4 Significance Tests: t-tests for two independent samples

Virtual delays at C2 with/without bus influence

H_0: The means of the two samples are identical. $|\mu_X-\mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X-\mu_Y| > 0$

virtual delays at C2		**μ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: outside of bus influence	1.05	1.296	1.680	1154	1153
Y	Sample 2: within bus influence	1.57	1.122	1.259	192	191

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	1.620
t:	t-statistic	-5.216
v:	degree of freedom	1344
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 1.96

Test: |t| > |q|

→ H_0 is rejected with a confidence level of 95%.

→ The means of the two samples are significantly different.

Virtual delay at C2 without bus influence, right/left lane

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

virtual delays at C2		**µ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: outside of bus influence, left lane	0.95	1.176	1.383	567	566
Y	Sample 2: outside of bus influence, right lane	1.14	1.502	2.255	587	586

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}} \frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	1.827
t:	t-statistic	-2.475
v:	degree of freedom	1152
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 1.96

Test: |t| > |q|

→ H_0 is rejected with a confidence level of 95%.

→ The means of the two samples are significantly different.

Virtual delay at C2 behind bus, right/left lane

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

virtual delays at C2		**µ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: behind bus, left lane	2.09	1.119	1.252	51	50
Y	Sample 2: behind bus, right lane	2.02	1.156	1.337	18	17

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}} \frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	1.273
t:	t-statistic	0.221
v:	degree of freedom	67
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 1.994

Test: |t| > |q|

→ H_0 is accepted with a confidence level of 95%.

→ The means of the two samples are not significantly different.

Delay at C3 with/without bus influence

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

delays at C3		**μ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: outside of bus influence	3.57	1.070	1.146	1101	1100
Y	Sample 2: within bus influence	3.53	1.203	1.447	171	170

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}} \frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	1.186
t:	t-statistic	0.424
v:	degree of freedom	1270
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 1.96

Test: $|t| < |q|$

→ H_0 is accepted with a confidence level of 95%.

→ The means of the two samples are not significantly different.

Delay at C3 outside of bus influence/next to bus

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

delays at C3		**µ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: outside of bus influence	3.57	1.070	1.146	1101	1100
Y	Sample 2: next to bus	4.09	1.741	3.030	30	29

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	1.194
t:	t-statistic	-2.590
v:	degree of freedom	1129
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 1.96

Test: |t| < |q|

→ H_0 is rejected with a confidence level of 95%.

→ The means of the two samples are significantly different.

Delay at C3 outside of bus influence/behind bus

H_0: The means of the two samples are identical. $|\mu_X-\mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X-\mu_Y| > 0$

delays at C3		**μ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: outside of bus influence	3.57	1.070	1.146	1101	1100
Y	Sample 2: behind bus	3.74	0.915	0.838	51	50

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x}-\bar{y}-\omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	1.132
t:	t-statistic	-1.140
v:	degree of freedom	1150
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 1.96

Test: |t| < |q|

→ H_0 is accepted with a confidence level of 95%.

→ The means of the two samples are not significantly different.

Delay at C3 next to bus capacity/non-capacity

H_0: The means of the two samples are identical. $|\mu_X-\mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X-\mu_Y| > 0$

delays at C3		**μ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: next to bus, capacity	3.54	2.995	8.969	4	3
Y	Sample 2: next to bus, non-capacity	4.21	1.458	2.127	26	25

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x}-\bar{y}-\omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	2.860
t:	t-statistic	-0.737
v:	degree of freedom	28
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 2.048

Test: |t| < |q|

→ H_0 is accepted with a confidence level of 95%.

→ The means of the two samples are not significantly different.

Capacity at C1 with/without bus influence

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

capacity at C1		**μ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: out of bus influence	2370.5	329.0	108261.8	50	49
Y	Sample 2: bus within capacity flow	2339.6	261.6	68436.0	10	9

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m + n - 2

s^2:	estimator of the common standard deviation	102082
t:	t-statistic	0.279
v:	degree of freedom	58
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 2.000

Test: $|t| < |q|$

→ H_0 is accepted with a confidence level of 95%.

→ The means of the two samples are not significantly different.

Capacity at C2 outside of bus influence/when bus flows behind capacity flow

H_0: The means of the two samples are identical. $|\mu_X-\mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X-\mu_Y| > 0$

capacity at C2		**µ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: outside of bus influence	4090	585.1	342363.1	56	55
Y	Sample 2: bus behind capacity flow	3760	457.0	208893.2	4	3

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x}-\bar{y}-\omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	335459.5
t:	t-statistic	1.101
v:	degree of freedom	58
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 2.000

Test: |t| < |q|

→ H_0 is accepted with a confidence level of 95%.

→ The means of the two samples are not significantly different.

Capacity at C2 outside of bus influence/when bus flows ahead

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

capacity at C2		**µ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: outside of bus influence	4090	585.1	342363.1	56	55
Y	Sample 2: bus within capacity flow	2611	232.9	54234.2	3	2

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	332253.3
t:	t-statistic	4.330
v:	degree of freedom	57
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 2.000

Test: $|t| < |q|$

→ H_0 is rejected with a confidence level of 95%.

→ The means of the two samples are significantly different.

Capacity at C3 outside of bus influence/when bus flows behind

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

capacity at C3		**μ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: out of bus influence	3963	587.7	345357.9	39	38
Y	Sample 2: bus behind capacity flow	3280	365.2	133387.9	3	2

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}} \frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	334759.4
t:	t-statistic	1.970
v:	degree of freedom	40
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 2.021

Test: |t| < |q|

→ H_0 is <u>accepted</u> with a confidence level of 95%.

→ The means of the two samples are <u>not significantly different</u>.

Capacity at C3 outside of bus influence/when bus flows ahead

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

capacity at C3		**μ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: out of bus influence	3963	587.7	345357.9	39	38
Y	Sample 2: bus in front of capacity flow	2643	70.4	4955.9	2	1

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	336629.6
t:	t-statistic	3.139
v:	degree of freedom	39
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 2.021

Test: $|t| < |q|$

→ H_0 is rejected with a confidence level of 95%.

→ The means of the two samples are significantly different.

Capacity at C2/C3 outside of bus influence

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

capacity		**μ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: outside of bus influence, C2	4090	585.1	342363.1	56	55
Y	Sample 2: outside of bus influence, C3	3963	587.7	345357.9	39	38

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m + n - 2

s^2:	estimator of the common standard deviation	343586.8
t:	t-statistic	1.040
v:	degree of freedom	93
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 1.987

Test: |t| < |q|

→ H_0 is accepted with a confidence level of 95%.

→ The means of the two samples are not significantly different.

Capacity at C2/C3 when bus flows behind

H_0: The means of the two samples are identical. $|\mu_X - \mu_Y| = 0$

H_1: The means of the two samples are not identical. $|\mu_X - \mu_Y| > 0$

capacity		**μ**	**s**	**s^2**	**n**	**n-1**
X	Sample 1: bus behind cap. flow, C2	3760	457.0	208893.2	4	3
Y	Sample 2: bus behind cap. flow, C3	3280	365.2	133387.9	3	2

$$s^2 = \frac{(n-1)s_x^2 + (m-1)s_y^2}{n+m-2}$$

$$t = \sqrt{\frac{nm}{n+m}}\frac{\bar{x} - \bar{y} - \omega_0}{s}$$

v = m+ n - 2

s^2:	estimator of the common standard deviation	178691.1
t:	t-statistic	1.487
v:	degree of freedom	5
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 2.571

Test: $|t| < |q|$

→ H_0 is accepted with a confidence level of 95%.

→ The means of the two samples are not significantly different.

A 5 Significance Tests: t-tests for two dependent samples

Non-capacity headway shift between C1 and C2

H_0: The difference of averages of two samples is not significant. $|X_D| = |\mu_0|$

H_1: The difference of averages of two samples is significant. $|X_D| > |\mu_0|$

non-capacity flow		**X_D**	**s_D**	**n**
D	flow shift C1-C2	-0.18	0.958	388.000

$$t = \frac{\overline{X}_D - \mu_0}{s_D/\sqrt{n}}$$

v = n-1

μ_0:	constant to be chosen	0.00
t:	t-statistic	-3.664
v:	degree of freedom	387
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 1.960

Test: $|t| < |q|$

→ H_0 is <u>rejected</u> with a confidence level of 95%.
→ The difference of averages of the two samples is <u>significant</u>.

Non-capacity headway shift between C1 and C3

H_0: The difference of averages of two samples is not significant. $|X_D| = |\mu_0|$

H_1: The difference of averages of two samples is significant. $|X_D| > |\mu_0|$

non-capacity flow		**X_D**	**s_D**	**n**
D	flow shift C1-C3	-0.24	1.223	273.000

$$t = \frac{\overline{X}_D - \mu_0}{s_D/\sqrt{n}}$$

v = n-1

μ_0:	constant to be chosen	0.00
t:	t-statistic	-3.283
v:	degree of freedom	272
α:	level of significance	95%
F(q):	probability density function of t-distribution	0.975
q:	quantile value of the t-distribution (out of table)	+/- 1.960

Test: $|t| < |q|$

→ H_0 is <u>rejected</u> with a confidence level of 95%.

→ The difference of averages of the two samples is <u>significant</u>.