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# Investigating the behaviors of cyclists and pedestrians under automated shuttle operation

Yun-Pang Flötteröd[1][https://orcid.org/0000-0003-3620-2715], Iman Pereira[2], Johan Olstam[2], and Laura Bieker-Walz[3]

[1] Institute of Transportation Systems, German Aerospace Center, Germany
[2] The Swedish National Road and Transport Research Institute, Sweden
[3] Dataport, Germany
Yun-Pang.Floetteroed@dlr.de, Iman.Pereira@vti.se, Johan.Olstam@vti.se, Laura.Bieker-Walz@dataport.de

**Abstract**

To understand the influence of the automated shuttles on active modes as pedestrians and bicyclists, data was collected at the pilot site Linköping within the context of the European project SHOW, where AS provide regular transport service on the campus and run along a corridor restricted to bike and pedestrian traffic with pre-defined stops. Three types of data were collected, i.e. video data, shuttle data and traffic count with use of Telraam, while the first one was the main data source for analyzing VRU behaviors and the others were used for checking the validity of video data. The investigation mainly focused on VRU's space usage, speed, acceleration and lateral position and distance with and without AS presence. Bikes maneuvers, compatible with overtaking, were also examined. The analysis results can help for simulation model improvement.

# 1 Introduction

The aim to introduce automated shuttles (AS) into daily life is to extend and enhance mobility quality and services as well as improve user experiences. It is also expected to increase accessibility not only in the temporal and spatial respects, but also in the aspect of user groups. Accordingly, more and more demonstrations take place for examining the respective impacts for further improvement on AS planning and operation. In some of demonstrations, active modes as pedestrians and bicyclists share space with AS. Due to the current regulations in many European countries and requirements on safe operations on and/or from the manufactures most AS run at low speed. Under such condition, AS's performance and possible contribution on transport system are limited as well. Furthermore, the introduction of automated shuttles on bike paths might imply additional interactions and delays for bicycle traffic. To analyze the interactions and potential delays the movements can be recorded via camera systems with computer vision, generating trajectories. However, there is also a need to investigate how the effects depend on the penetration rates and possible operation speed of the AS.

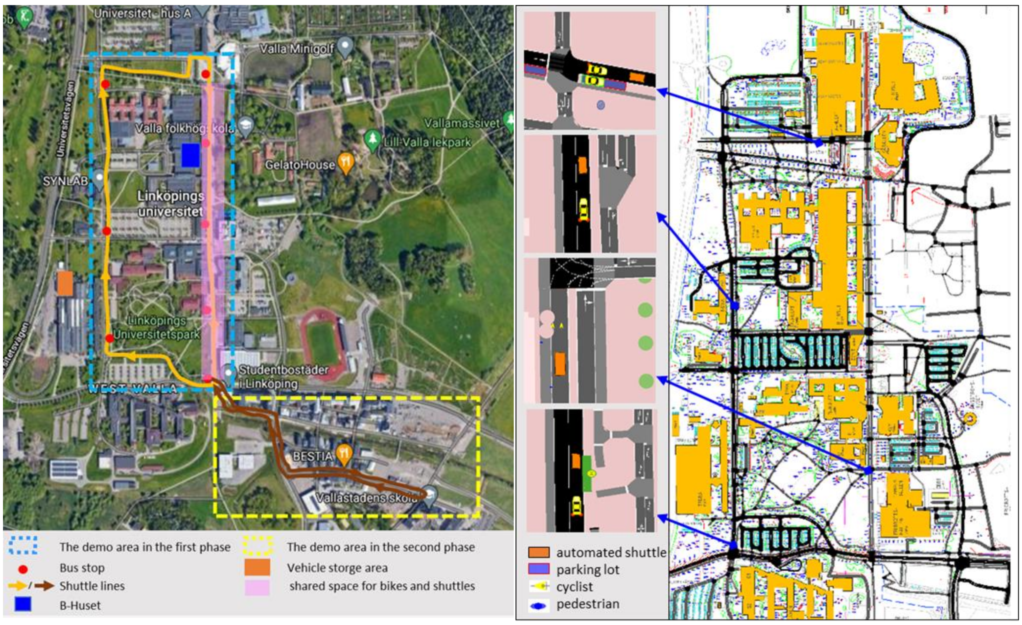
Traffic simulation is a suitable supplementary instrument for evaluating AS's impacts under different conditions given that models in traffic simulation can properly represent road users' behaviors. In this paper, extracted trajectory data from video data, collected in the shared space at the test site Linköping, was analyzed with the following aims

- to better understand the general influence of the AS introduction on VRU;
- to extract key pedestrian and bike related parameters/characters for enhancing simulation models, such as desired speed distributions for pedestrians and bikes, clearance distances between pedestrians, bikes and AS and maneuvers related to overtaking actions.

Apart from the video data, trajectory and operation data, collected by AS, and traffic count and speed data collected by Telraam [1] was also used for cross-checking the data validity and for gathering traffic demand for a longer time period for future upcoming traffic simulation experiments.

# 2 Test site Linköping

Test site Linköping is a part of the Swedish twin mega sites [2] within the European project SHOW [3]. The main objectives are to improve user experience and to provide a robust first and last mile solution to public transportation. The test site's overall layout is illustrated in Figure 1(a), and it is divided into two parts according to the demonstration phases. The first part is the university campus as surrounded by the blue dotted line. During the data collection period two AS ran in clockwise direction with maximum speed 14 km per hour, whilst there are three AS in operation currently. They serve 8 pre-defined locations, indicated as red dots. The planned AS schedule is 20 minutes. The second part is the adjacent residential area, as bounded by the yellow dotted line.




(a) Layout of the test site Linköping (b) Simulation network of the campus area

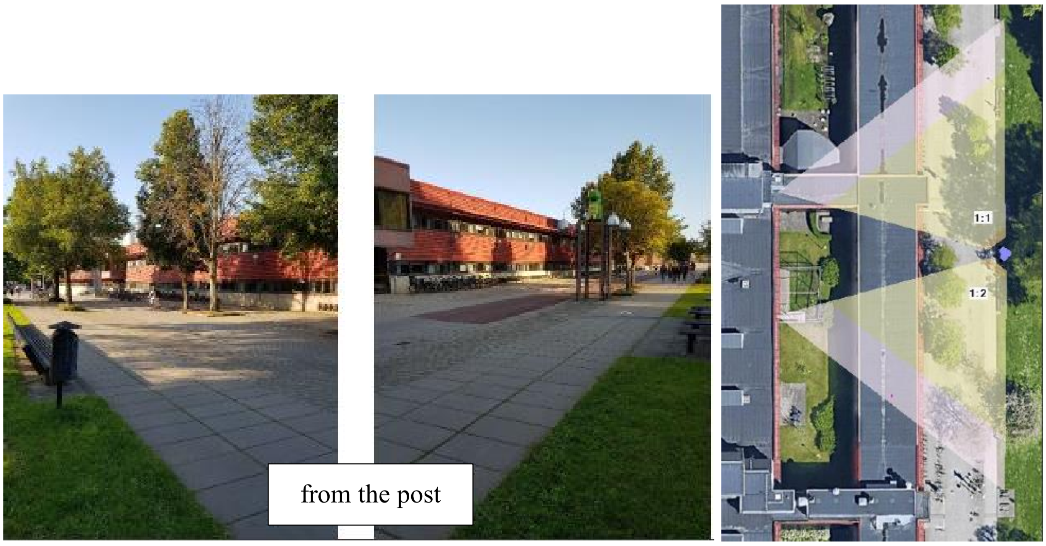
**Figure 1:** Overview of Test Site Linköping

The data analysis and the ongoing simulation work with SUMO [4] focus on the campus area (see Figure 1(b)) [5, 6, 7]. The analyzed video data was collected at the B-Huset in the shared space on the eastern side, marked in pink in Figure 1. In this area, cyclists and shuttles share the bike path, located in the middle of the space, and pedestrians can cross the bike path anytime if necessary. All intersections on campus are priority-controlled intersections.

# 3 Data processing and verification

Data was collected from three sources, i.e. video-camera based measurement system from Viscando, Telraam and log data from the AS, and is briefly explained below.

- Shuttle data: it consists of the AS trajectory information, i.e. timestamp, position expressed in longitude and latitude and speed, and the operational data, such as status of the vehicle door, battery level, load information, operation mode (manual or automatic), etc. The latter one is irrelevant to this study scope.
- Telraam data: it contains the number of passages per type over a cross-section at B-Huset in the shared space. In addition, the counts are given together with an estimate of the speed and the direction of which the object is moving.
- Viscando data: the measuring site was chosen in the middle of the shared space corridor with the consideration of the road infrastructure and the locations of lamp posts. Two OTUS3D cameras from Viscando were deployed. Figure 2 and Figure 3 show the space layout and the coverage overview from the video cameras.




Source: [8] and Google Map (right)

**Figure 2:** Space layout of the measuring site

Data from shuttles and the OTUS3D cameras were available for the entire study period from the 20th of September 10:00 AM to the 26th of September. As the Telraam counter was set up later, data from the counter is available from the 22nd of September 12:00 AM to the 26th of September. Since the shuttles did not operate during weekends and evenings, the study period is from the 22nd to the 24th of September between 8:00 and 18:00.

The OTUS3D cameras captured all road users in the area with the highest attention to detail. Thus, this is considered to be the main data source used for analysis. Both the shuttle data and the Telraam data were mainly used for verification purposes as both data sources were very limited for the purpose of studying variations in traffic performance of bicyclists with and without shuttle presence.

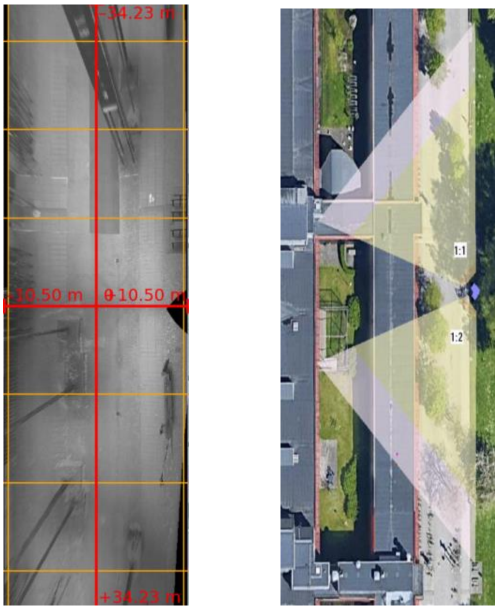
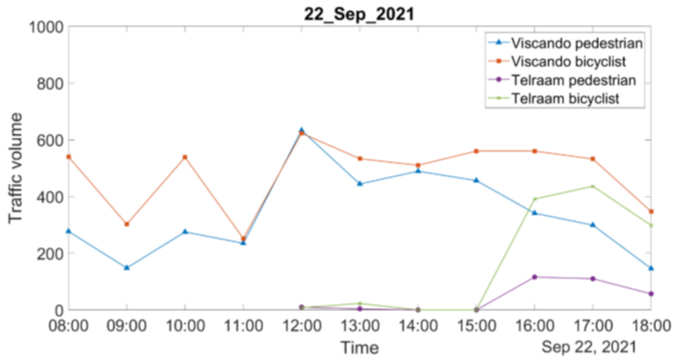



**Figure 3:** Coverage overview of the measuring site from the video cameras **[8]**

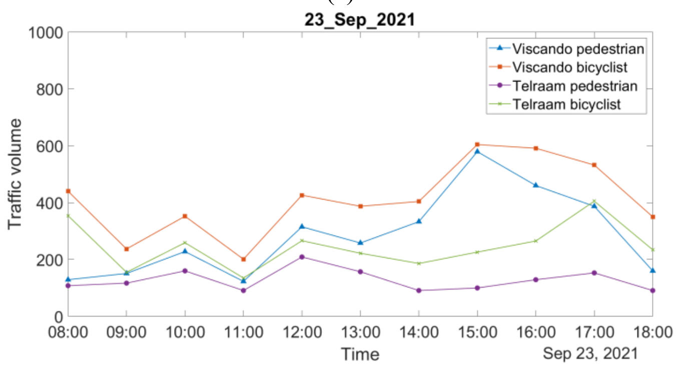
Furthermore, the OTUS3D camera data was processed and cleaned due to some misclassifications (only for AS), ghost trajectories, trajectory fragmentation with temporal/spatial jumps and short trajectories. All trajectories shorter than 9 meters were excluded. Pedestrian trajectories with space jump larger than 3 meters, and bicycle trajectories with space jump larger than 6 meters were also excluded. Lastly, trajectories with inconsistencies in time sampling rates were split if time jump exceeded 3 seconds. In the end, data was split into two groups: (1) Data set 1 – Trajectory data when a shuttle was present, and (2) Data set 2 – Trajectory data when no shuttle was present.

The time periods with shuttle presence were relatively short, causing an imbalance in the amount of data between the two datasets. Also, the shuttles were not always detected correctly, and the corresponding amount was underestimated (10% - 40% daily in the whole study period) when comparing with the ground truth shuttle data. In the end, the data set with shuttle presence is naturally smaller and constitutes 2% of the entire data set. Approximately 15% and 11% of the data in the data sets 1 and 2 were not used for analysis respectively.

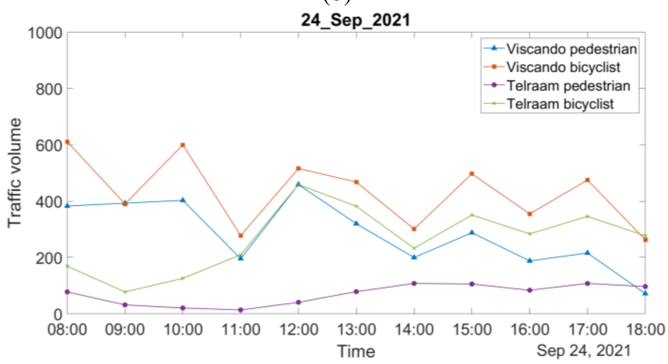
In addition, the flow comparison between Viscando data and Telraam data was also carried out. Figure 4 (a), (b) and (c) show that the Telraam counter consistently underestimated the traffic volume in comparison to the Viscando system with regards to pedestrians and bicyclists. It implies that Telraam counter, which is developed to count passages over a cross section, seems to have difficulty to handle traffic counting in a shared space where objects move more freely than those on normal roads. However both systems show that traffic peaks appeared around 12:00 PM, and close to 17:00 PM, which coinsided with lunch break and the last lecture given at the university.




(a)




(b)




(c)

**Figure 4:** Hourly traffic volumes detected by Viscando and Telraam

# 4 Data analysis

## 4.1 Space usage

As mentioned in Section 2, the shared space was originally designed to be used by pedestrians and cyclists, and has then also been used by AS since 2020, where cyclists and AS share the bike path. Figure 5 shows the collected trajectories by type and direction when AS were present. The directions of pedestrian and cyclist flows were mainly from north to south and from south to north, whilst the AS ran only from north to south. It also shows that both pedestrian and cyclists mainly used their respective designated paths, but did deviate from these to some extent using each other's paths as well.

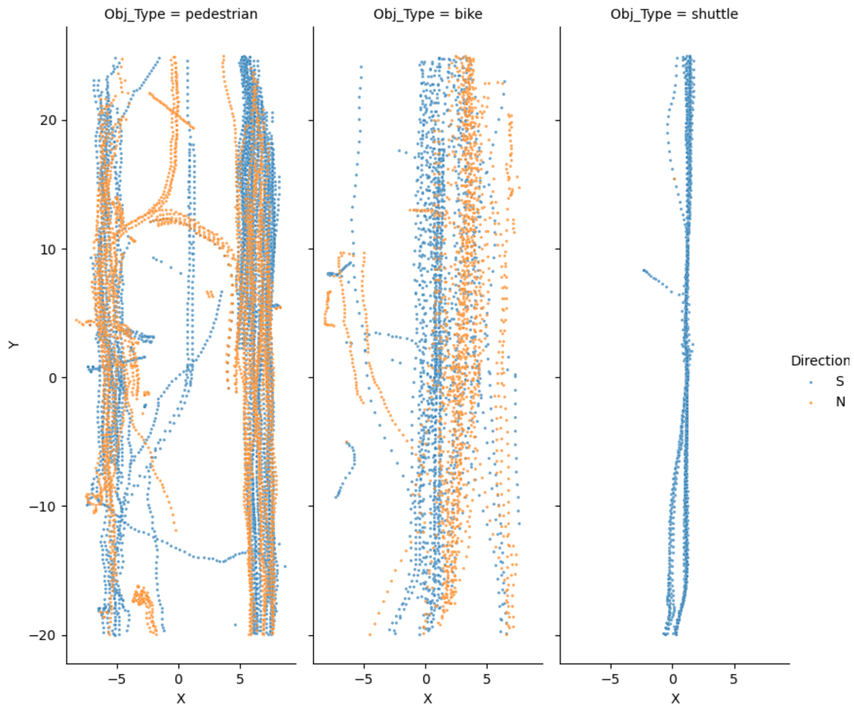



**Figure 5:** Object trajectories when shuttle was present

The usage of bike path with and without the AS presence was further analzed. The result in Table 1 shows that AS ran 99.5% within the bike path as expected, and their paths deviated from the pre-defined path sometimes due to unexpected events, which can also be oberseved from their trajectories in Figure 5. The pedestrians tended not to use the bike path even when the AS were not present. The percentage of pedestrains using the bike path slightly decreased from 7.2% to 5.3% when the AS were present. In comparison to that, the decreasing rate for cyclists reached around 20%, while 68% of cyclists used the bike path without AS presence. It indicates that cyclists were those directly affected by the AS introduction. Pedestrians were also affected due to that cyclists use then more often the sidewalks with the AS presence.

| X position (m) | Type | with shuttle presence | without shuttle presence |
|---|---|---|---|
| -2 <= x <= 2 | AS | 99.5% | - |
| (within bike | pedestrian | 5.3% | 7.2% |
| path) | bike | 47.0% | 68.2% |

**Table 1:** Changes in space usage with and without shuttle presence

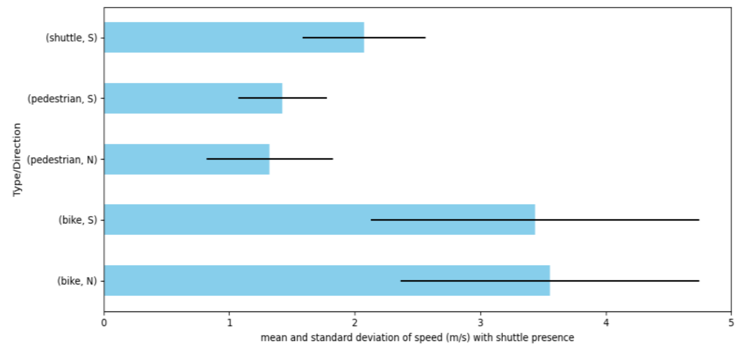
## 4.2 Speed and acceleration

To understand the influence of the AS introduction on the motions of pedestrians and bikes, mean speed, mean acceleration and the respective standard deviations for each object type were analyzed. The result is summarized in Table 2 and illustrated in Figure 6. It shows that the mean speed of bikes was slightly higher when traversing through the study area in the same direction as the shuttle in comparison to that when bikes were moving in the opposite direction of the shuttle. This is not entirely unexpected as there is a slight slope in the north part of the study area. Therefore, bikes entering the study area from the north might have gained a little speed. It also shows that bikes tended to slow down in both directions when the shuttles were present. However, such slow-down is not statistically significant according to the t-test result with a significance level of 0.05.

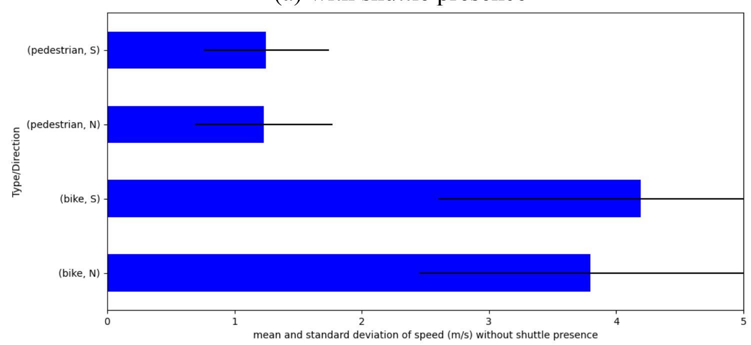
| AS presence | type | Southbound (AS's running direction) | | | | Northbound | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | mean speed | speed s.d.* | mean acc.* | acc s.d.* | mean speed | speed s.d.* | mean acc.* | acc s.d.* |
| Yes | ped. | 1.4244 | 0.3526 | -0.0003 | 0.3935 | 1.3231 | 0.5057 | 0.0139 | 0.4541 |
| | bike | 3.4367 | 1.3088 | 0.0149 | 0.8962 | 3.5557 | 1.1880 | 0.0624 | 0.8669 |
| | AS | 2.0756 | 0.4902 | -0.0247 | 0.6269 | - | - | - | - |
| No | ped. | 1.2503 | 0.4911 | 0.0022 | 0.4044 | 1.2306 | 0.5394 | -0.0016 | 0.6261 |
| | bike | 4.1919 | 1.5903 | 0.0077 | 0.9128 | 3.7995 | 1.3492 | 0.0386 | 0.7294 |

*: s.d.: standard deviation; acc: acceleration

**Table 2:** Mean speed and acceleration by type and direction with and without AS presence




(a) with shuttle presence




(b) without shuttle presence

**Figure 6:** Mean speed and standard deviation per type and direction with and without AS presence

Regarding pedestrians' speed it seems that there was a small tendency for pedestrians to walk slightly faster when the shuttle was present. According to the t-test the mean speed difference is statistically significant at a confidence level of 0.05. It could potentially mean that pedestrians got a sense of urgency when the shuttle was present and therefore walked slightly faster. Moreover, there were substantially fewer crossings while the shuttle was present. Thus, another possible reason could be that speeds during straight walking are faster than those during crossing. In any case it is hard to know exactly why the data shows this unexpected result and would need deeper investigations.

When looking at the accelerations both pedestrians' and bikes' mean accelerations were around 0 $m/s^2$ either with or without the AS presence, and no statistically significant difference exists between the mean accelerations with and without the AS presence for both object types.

The illustration in Figure 7 gives a clear overview about the speed-acceleration relationship of each object type when AS were present. AS's speed spectrum was similar to the pedestrians' speed spectrum (between 0 and 3 m/s), whilst bikes' speed spectrum was relatively wider. The acceleration spectrum was mainly between 1 and -1 $m/s^2$ for all object types. A few of pedestrians' accelerations were close to 2 or -2 $m/s^2$. It could be due to the misclassification or measurement errors.

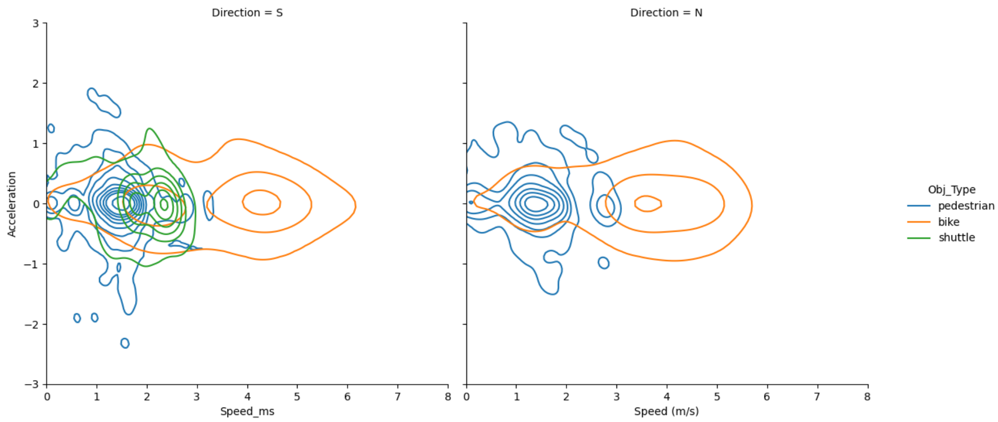
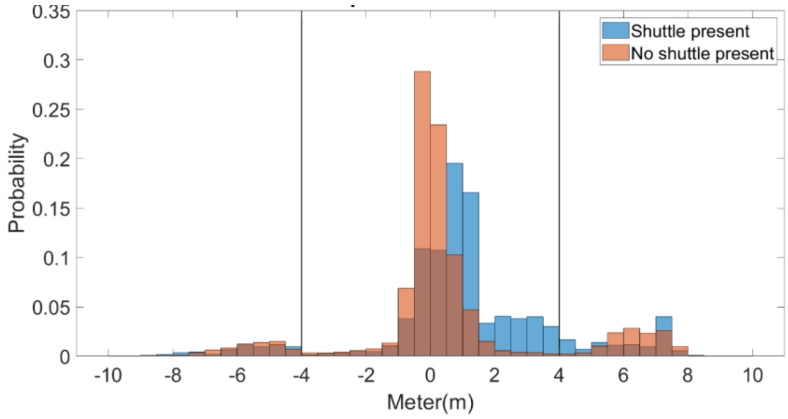



**Figure 7:** Relationship between speed and acceleration per type and direction with the AS presence

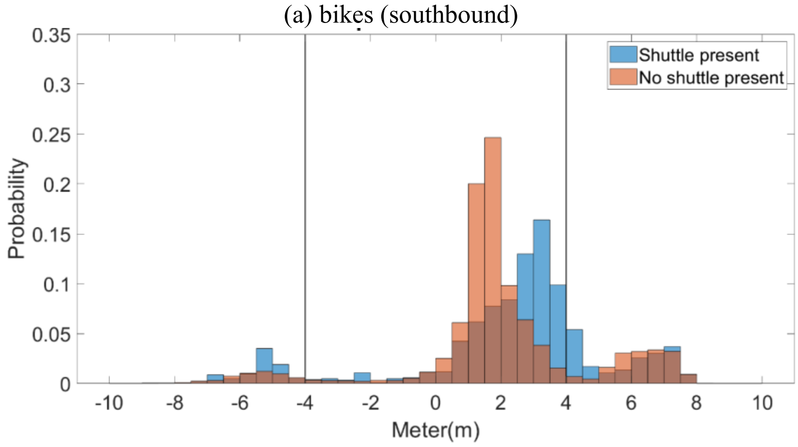
## 4.3 Lateral position and distance

Figure 8 (a) and (b) show lateral positions of bikes and pedestrians for the case when a shuttle is present and the case when no shuttle is present. Both figures show that bi-directional bicycle traffic shifted to the same direction, i.e. to the east of the shuttle, when the shuttle was present. It seems as the sidewalk shift was larger for the southbound bikes than for the northbound bikes. In addition, it seems that bikes travelling in the opposite direction of the shuttle tended to encroach the sidewalks more than those travelling in the shuttle's running direction. On the contrary, pedestrians still mostly walked or stood on the pedestrian paths although some pedestrian activities occurred on the bicycle paths as well. There is not much of a difference in the two studied situations although there seemed to be a slight increase in the probability to choose the pedestrian paths when the shuttle was present. These findings correspond to the result shown in Section 4.1 space usage.

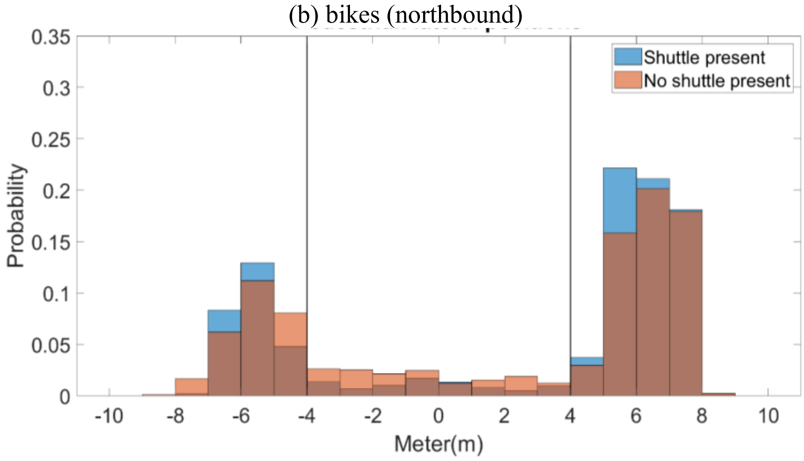
Moreover, the lateral distances in relation to the longitudinal distances between objects and AS were also examined. Figure 9 depicts that pedestrians mostly kept at least a lateral distance 3 m away from




(a) bikes (southbound)



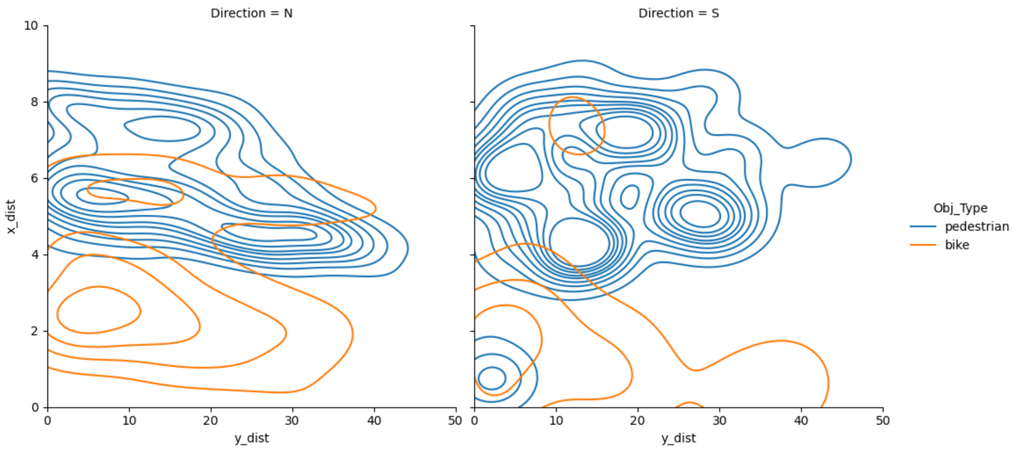

(b) bikes (northbound)




(c) pedestrians (both directions)

**Figure 8:** Bikes' and pedestrians' lateral positions with the AS presence

the shuttles' x positions in the shuttles' running direction. When the longitudinal distance between pedestrians and shuttles was less than 10 m, the respective lateral distance increased to mostly more than 4 m. In the opposite northbound direction, the minimum lateral distance was around 3.8 m, and it increased to more than 4 m with a longitudinal distance less than 10 m. In comparison to that, the lateral distances of the southbound bikes varied between 0.4 m to 4.3 m within 10 m longitudinal distance, and tended to decrease when the longitudinal distance increased, i.e. cyclists tended to move back to the bike path when they are getting far away from the shuttles. In addition, it seems that bikes' lateral distances to the shuttles' x positions varied quite large even when the respective longitudinal distance less than 10 m. The minimum lateral distance within 10 m longitudinal distance was around 0.8 m. In addition, there is a tendency for cyclists to decrease their lateral gaps when their longitudinal gaps increase in the southbound direction, but not in the northbound direction.




*: x_dist: lateral gap (m) between object's and shuttle's x-positions; y_dist: longitudinal gap (m) between object's and shuttle's y-positions

**Figure 9:** Lateral distances in relation to the longitudinal distances between the objects and the AS

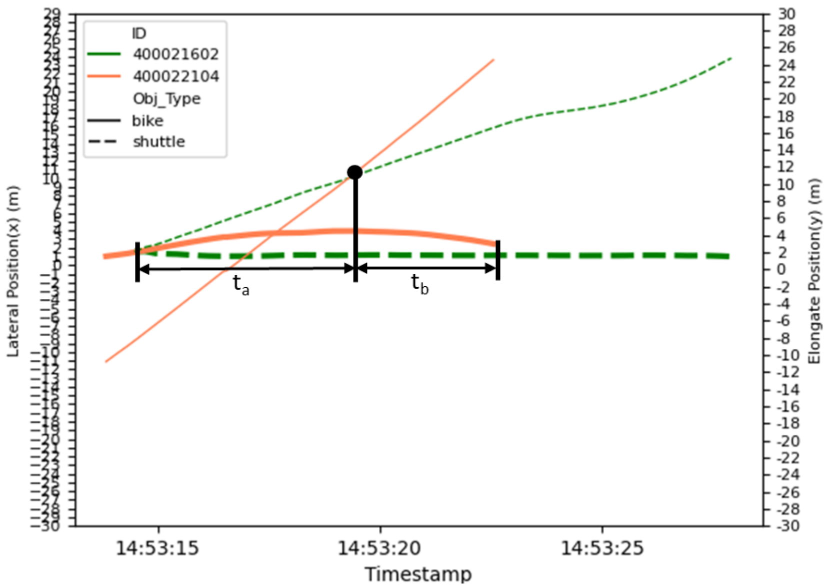
## 4.4 Interactions between objects and shuttles

Interactions between objects and shuttles cannot be observed from extracted trajectory data, only the maneuvers resulting from cyclists/pedestrians intending to take. Accordingly, only the corresponding action points, not decision points, can be discovered. Some interactive maneuvers, compatible with yielding, following, and overtaking, were observed according to the respective time-space diagrams. Such interactive maneuvers appeared quite rarely in the study area during the whole data collection period. Most of them were between bikes and shuttles, since pedestrians mainly used sidewalks. The mainly identified maneuvers were the maneuvers related to overtaking and conflict avoiding in the southbound and northbound directions respectively. Accordingly, the required time distribution for such maneuvers can be derived from the corresponding time-space diagrams.

A. Overtaking maneuvers

The concept to derive the afore mentioned duration distribution is to firstly identify the object candidates which fulfill the pre-defined criteria corresponding to an overtaking maneuver. The proposed criteria consist of (1) an object catches and passes the respective shuttle at a certain time point within the same time window, i.e. there is a cross point in the respective y-positions-based time-space diagram; (2) the x-position of the object in (1) gets closer and closer to the shuttle's x-position over time after catching the shuttle; and (3) the x-position of the object in (1) begins to get farther away from its previous x positions and the shuttle's x-position at some certain time point before catching the shuttle. After that, the time ($T_{overtake}$) spent for the whole overtaking-related maneuver is divided into two parts:

- $t_a$: duration between the point when a bike catches up with a shuttle, i.e. reaching the same y position, and the point when this bike begins to deviate its path from the shuttle path (see Figure 10).
- $t_b$: duration between the point when a bike catches up with a shuttle, i.e. reaching the same y position, and the point when this bike moves back to the bike path (see Figure 10).




*: fat dash line: shuttle's x positions; thin dash line: shuttle's y positions; fat solid line: bike's x positions; thin solid line: bike's y positions.

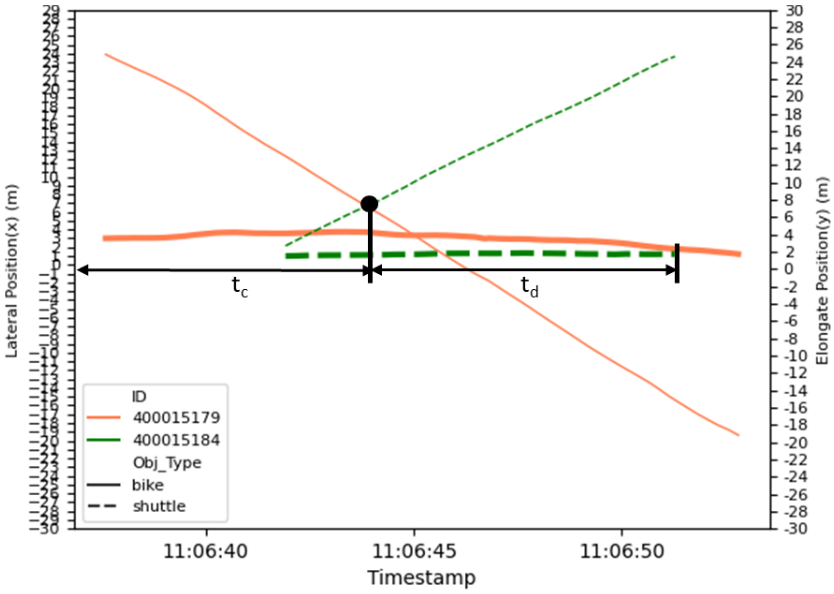
**Figure 10:** Time-space diagram of the exemplary objects with overtaking maneuver

B. Maneuvers to avoid conflicts

Following the similar concept in Section A objects are selected as candidates when their maneuvers correspond the following characters: (1) An object is coming towards the shuttle running in the opposite position; (2) The object in (1) deviates his/her path from the bike path before meeting the shuttle (move-out); and (3) The x-position of the object in (1) gets closer and closer back to the bike path, i.e. shuttle's x-position) over time after meeting the shuttle (move-back). The time ($T_{avoid}$) spent for the whole maneuver is also divided into two parts, just like $T_{overtake}$:

- $t_c$: duration between the point when a bike meets a shuttle at the same y position and the point when this bike begins to deviate it path from the shuttle path (see Figure 11).
- $t_d$: duration between the point when a bike meets a shuttle at the same y position and the point when this bike moves back to the bike path (see Figure 11).

The reason for the time separation is due to incomplete trajectory data or/and trajectory fragmentation, which can be seen in Figure 11 as example. Moreover, data interpolation will be applied as well in order to get more samples. Accordingly, the respective duration distributions can be derived. The implementation work is currently undertaken.




*: fat dash line: shuttle's x positions; thin dash line: shuttle's y positions; fat solid line: bike's x positions; thin solid line: bike's y positions.

**Figure 11:** Time-space diagram of the exemplary objects for avoiding conflicts

# 5 Conclusion and perspective

Video-camera based measurements has been used for traffic data collection since years due to its efficiency and effectiveness for temporally and spatially collecting large amount of road user movements. Various processing methods have been developed and commercialized. With the consideration of data protection respective image resolution is normally limited and it can result in some imprecision in data extraction especially when other conditions are not adequate, such as light, visibility, monitoring position and the complexity of movements. In this study, some imprecise data exists in the extracted trajectory data, and it could be resulted from several situations, e.g. (short) incomplete trajectories du to shuttles blocked the objects behind, double counting due to shadow effect, misclassification due to that pedestrians walked with bikes or they were too close to each other. According to the comparison result with the ground truth shuttle data approximately 70% of the shuttle passages were captured correctly. Moreover, the analysis of pedestrian and bicycle trajectories resulted in an error between approximately 11% and 14% depending on the dataset. Since there are only anonymized videos available for pedestrians and bicyclists, it is harder to correctly identify all the errors. It is assumed that uncertainties in the data still exist after data filtering. In addition, Telraam counter seems to have difficulty to properly count the passages of each object type in a shared area where pedestrians and bikes can move more freely than standard roads.

According to the analysis results bikes were the main objects directly affected by the AS introduction. They tended to encroach sidewalks when the shuttles were present. Pedestrians tended to continue using sidewalks and were possibly then affected by the changed movements of the bikes accordingly. The shuttle presence did not statistically significantly affect the acceleration behaviors of either pedestrians or bikes. However, the mean speeds of both road users were slightly affected by the shuttle presence. Bikes tended to traverse the area with a lower mean speed while the shuttle was present. The possible reasons could be that bicycles got hindered by the shuttles operating on the bike path or/and cyclists were not being able to travel at their desired speed due to the reduction in available space (with AS presence). In contrast to the bikes, there was an increase in pedestrians' mean speed with statistical significance when the shuttles were present. Despite of the result of statistical significance the amount of speed increase is very limited (0.17 m/s southbound and 0.09 m/s northbound). Together with the consideration of (1) no difference in acceleration behavior and (2) little difference in lateral positioning it would be difficult to observe or feel a real speed difference while walking throughout the area. Further investigation is then needed. Moreover, interactive maneuvers between objects and shuttles were examined with use of time-space diagrams. Only quite limited maneuvers, compatible with yielding, following and overtaking, were observed, while the latter one occurred more often.

In this paper, the focus puts on if there is any influence on the selected performance indicators (speed, acceleration, space usage) with the AS introduction. A concept to derive the duration distributions for the time spent for overtaking-related maneuvers is proposed. The respective implementation work is undertaken. In the next step, the interactions between pedestrians and bikes under the AS presence will be investigated. Moreover, several parameters, such as speed/acceleration distributions, durations for overtaking-related maneuvers will be derived and comparisons with simulated data will be carried out for examining and enhancing the respective microscopic traffic modelling. If the data is sufficient, the focus will be further put on the use of Bayesian inference to model the decision of the maneuver compatible with overtaking.

# 6 Acknowledgement

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