TØI rapport 1822/2021

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Performance of automated shuttles at signalized intersections

Video analyses of three intersections in Rådhusgata in Oslo centre

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Sammendrag:

Selvkjørende busser testes over hele verden. De fleste slike piloter foregår i avgrensede og kontrollerte områder eller i områder med enkle trafikkforhold. Denne rapporten gir en unik evaluering av hvordan selvkjørende busser reagerer i ulike situasjoner under mer komplekse forhold. Driften av bussene i tre signaliserte kryss i Oslo sentrum er undersøkt ved hjelp av eksterne videoobservasjoner under reelle trafikkforhold. Funnene gir verdifull kunnskap om bussenes reaksjoner på trafikksignalene og til andre trafikanter. Slik kunnskap kan brukes videre i andre forsøk med automatiserte kjøretøy.

Summary:

Automated shuttles are being tested frequently worldwide. Most such pilots take place in more-less controlled environment or in areas with simple traffic conditions. This report provides a unique evaluation of the performance of the shuttles in more complex urban environment. The operation of the shuttles at three signalised intersections in Oslo centre has been investigated using external video observations under real traffic conditions. The findings provide valuable knowledge regarding shuttles’ reactions to the traffic signals and to other road users. Such knowledge can be utilized in other pilots with automated vehicles.

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Preface

Public transport provider Ruter has tested automated shuttles in Oslo through several pilots. For further adoption of these shuttles in normal traffic, it is important to test and evaluate their performance at signalized intersections. The purpose of this project has therefore been to register and analyze how automated shuttles handle driving through traffic lights in central Oslo (Rådhusgata), and what challenges this may entail.

The project is a collaboration between Institute of Transport Economics (TØI), Ruter, the Norwegian Public Roads Administration (NPRA), Oslo Municipality and Holo. The project is funded by NPRA and TØI's own funds.

The project partners' contact persons have been Lars Gunnar Lundestad and Helene Otterdal from Ruter, Magnus Larsson, Irina Jonsson, Johnny Benn Hansen, and Ørjan Tveit from NPRA, Reidun Hauken and Sesilie Bjørdal from Oslo Municipality and Hans Fridberg from Holo.

At TØI, Petr Pokorny has had the main responsibility for collecting and analyzing data, and for writing the report. In addition, Belma Skender and Espen Johnsson give advice during the analyzes. Torkel Bjørnskau has been the project manager. Trine Dale has been responsible for the quality assurance of the report, Trude Rømming has prepared the report for publication.

Oslo, January 2021

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Selvkjørende busser testes over hele verden. De fleste slike piloter foregår i avgrensede og kontrollerte områder eller i områder med enkle trafikkforhold. Denne rapporten gir en unik evaluering av ytelsen til selvkjørende busser under mer komplekse forhold. Driften av bussene i tre signaliserte kryss i Oslo sentrum er undersøkt ved hjelp av eksterne videoobservasjoner under reelle trafikkforhold. Funnene gir verdifull kunnskap om bussens reaksjoner på trafikksignalene og på andre trafikanter. Slik kunnskap kan brukes videre i andre forsøk med automatiserte kjøretøy.

RUTER har sammen med Statens vegvesen og Oslo kommune testet selvkjørende busser på flere ruter i Oslo-regionen de siste to årene. En av disse rutene er i et indre byområde i Oslo, fra Vippetangen til Christiania Torv (#35). Ruten inneholder tre signalregulerte kryss i Rådhusgata, og dette prosjektets formål er å studere bussenes atferd og kommunikasjon med trafikklys i de signaliserte kryssene. På denne ruten var bussen i drift fra juni til september 2020. Bussen var en Navya Arma med automatiseringsnivå 3 i henhold til SAE-standarden.

Studien tok sikte på å undersøke bussens oppførsel og reaksjoner på andre trafikanter og på trafikksignalene, og også atferden til andre trafikanter i møte med bussen. Data ble innhentet ved hjelp av videoregistreringer. Tre kameraenheter ble installert i de tre signaliserte kryssene. Alle videoopptak med bussene ble gjennomgått og kategorisert etter plassering i kryssene, og etter bussenes og andre trafikanters atferd. Dette gjorde det mulig å identifisere uvanlige situasjoner og potensielle risikoer. Mange slike situasjoner involverte myke trafikanter.

Totalt ble det observert 408 busser, og i 170 situasjoner hadde bussen en form for interaksjon med andre trafikanter. Bussene har lav hastighet og en defensiv kjørestil. Bussene reagerte korrekt i de fleste møtene. I tillegg gjenkjente den flere brudd på trafikkreglene fra andre trafikanter og responderte adekvat, selv i komplekse situasjoner. Det ble ikke observert alvorlige konflikter.

Imidlertid var det situasjoner der bussen reagerte feil (umotivert stans i krysset osv.), samtidig som det ofte ikke var åpenbart hva grunnen til disse uventede og gale reaksjonene var. Slike uventede og uforutsigbare reaksjoner kan øke risikoen for andre trafikanter. Videre påvirket den defensive kjørestilen oppførselen til noen trafikanter, og i en del tilfeller gjorde de risikable manøvre for å plassere seg foran bussen.

Situasjonene da bussen møtte en endring i lyssignalene (spesielt fra grønt til rødt) nær stopplinjen, var ofte preget av feil reaksjon fra bussen. Dette skjedde enda oftere dersom det samtidig oppsto en annen utypisk og uventet situasjon (syklist mot kjøreretning el.l.).

Funnene gir verdifull kunnskap om selvkjørende bussers reaksjoner på trafikksignaler og reaksjoner på andre trafikanter i lyskryss. Slik kunnskap kan være nyttig i andre forsøk med automatiserte kjøretøy.

1 Introduction

1.1 Background

A considerable number of pilots with automated shuttle buses (AV shuttles) have recently been implemented in Europe and USA. Most of them have been carried out in form of demonstrations or pilots in simple and controlled traffic environments (Heikoop et al., 2020; Haque & Brakewood, 2020). However, for the further development of the AV shuttles (further referred as *the shuttles*), it is fundamental to test them and evaluate their performance in more complex traffic environments. In such environments the shuttles are exposed to unpredictable and unexpected situations, are experiencing encounters with other road users and must deal with traffic control devices, such as traffic signs and signals. Particularly safety aspects of their performance are key for societal acceptance and public adoption of these shuttles.

It is not possible to evaluate shuttles safety with the common measures (such as accident rates and risks), because only a very few accidents have been recorded. Claburn, (2019) describes two such accidents. In the first, a shuttle detected an obstacle and stopped abruptly, causing an elderly passenger to slip off the seat. In the second, a shuttle collided with a pedestrian, who, according to witnesses, was not paying attention and walked against the shuttle. Another accident has been in-depth analysed and reported by NTSB (2019). In this non-injury accident, the shuttle was on its designated path, while a backing trailer hit the shuttle. The report identified the truck driver 's action and his expectation that the shuttle would stop as the main contributory accident factors.

Since accidents are rare, proxy safety measures can be suitable alternatives to evaluate the safety of the shuttles (Fraade-Blanar et al., 2018). These are for example disengagements, infractions of traffic rules or surrogate safety measures related to traffic conflicts. However, so far, most of the studies on shuttles' safety have focused on the perception or acceptance of the shuttles, using survey-based methods and questionnaire-based experiments, while behavioral observation studies under real, unpredictable traffic conditions are lacking (Heikoop et al., 2020).

1.2 Research question

Public transport provider RUTER, together with the Norwegian Public Roads Administration (SVV), Oslo Municipality and the operator of autonomous vehicles, Holo, have been testing the shuttles on several routes under real traffic conditions in the Oslo region since 2019. One of these routes was in an inner-city area of Oslo. It contained three signalized intersections on Rådhusgata street, where the shuttles communicate with the traffic signaling system using V2X (vehicle to everything communication) without manual intervention from the shuttle steward / operator.

Obviously, there are a number of challenges associated with such communication, such as correct recognition of signals, timely and smooth reaction etc. Furthermore, there are other challenges related to the shuttle's behaviour and interactions with other road users. For example, based on recent Norwegian experiences with shuttles at Forus, Kongsberg and Akershusstranda, we know that risky and unexpected situations can arise when other road users drive past or overtake these shuttles (Bjørnskau et al., 2019). This happens relatively often since these shuttles run slowly. It is likely that this will be an issue also on this route in Oslo city center, and perhaps especially on the approach to the signalized intersections since the shuttles will have to pass the intersections slower than other vehicles. The typical defensive driving style of automated vehicles can also cause shuttles to stop at traffic lights, while other road users following behind the shuttle expect them to drive. Experiences with automated vehicles in the US show that rear-end collisions are the most common type of accidents in which such vehicles are involved (Biever et al., 2020).

In order to succeed with good operation through the three signalized intersections on Rådhusgata and draw learning from it, it is crucial to gain knowledge about the performance of the shuttles. Furthermore, it is important to evaluate how other road users react to the shuttles' behaviour along the intersections' approaches/exits and at the traffic lights. In addition, there is a need to investigate such matters both nationally and locally. The reactions of other road users to how such shuttles behave at traffic lights will probably to a very large extent be determined by the national and possibly local traffic culture. This means that there is a need for new knowledge about this in Norway, and specifically there is a need to investigate this on the new route(s) that have been launched in Oslo.

Therefore, the Institute of Transport Economics (TØI) has received research funding from the Norwegian Public Roads Administration (NPRA) to conduct this study. The study was part of a collaboration between TØI, RUTER, SVV, Oslo municipality and Holo. Specifically, it aims at investigating the following:

1. The shuttle's behaviour and its reactions to other road users
2. The shuttle's behaviour in relation to traffic signals
3. Behaviour of other road users in encounters with the shuttles

There may also be other issues and insights that the study will be able to uncover. Altogether, it should provide valuable knowledge that can be utilized further in other experiments with automated vehicles, such as the pilot that RUTER is planning in Ski.

2 Method

The method applied in this study is based on the analysis of external video recordings of shuttles' performance on all three signalized intersections. The original intention was to compare the performance of the shuttles operating in level 3 automated mode **without** (weeks 27-28) and **with V2X communication** (weeks 35-36). However, this was not possible, because the shuttles were not operating in any automated mode in weeks 27-28. The reason was that shuttle operators very soon discovered that the shuttle without V2X did not perform well on the traffic lights, experiencing unexpected stops, delays at intersections and in general an unpredictable behaviour. The shuttle operators judged this to be problematic and risky and took over control. Therefore, only weeks 35-36, when the shuttles were driving in the automated mode and all intersections were already equipped with V2X units, were considered in this study.

2.1 The route

The studied route was #35 from Vippetangen up Kongens gate to Christiania Torv and back (Fig. 1 - right). The route (1,4 km long in one direction) was established in such way that it was, among others, possible to study the performance of the shuttles and their communication with traffic lights at three signalized intersections in Rådhusgata. On this route, the shuttle was in operation from June to September 2020, every week from Thursday to Sunday, from 09:30 to 20:30, scheduled approximately every 30 minutes[1]. The brand of the shuttle was Navya Arma with level 3 automation according to SEA standards[2] (SEA, 2018). For some of the shuttle's parameters, see Fig. 1 (left).

- Capacity: 8 passengers (+ "a driver")
- Speed: 18km/h
- Dimensions: 4.75m long, 2.11m wide and 2.65m tall

Technology

- LIDAR (8 sensors, 4 front and 4 back)
- Global Navigation Satellite System GNSS; Odometer; An inertial measurement unit (IMU)

Figure 1 - The parameter of the shuttle (left, source: www.ruter.no) and the studied route (right)

[1] *There were some irregularities in the number of shuttles driven per day in some periods, experienced due to technical/operational problems.*

[2] *The shuttles drove in an automatic mode, however in situations that required performing an unstandardized maneuver (such as passing a vehicle parked in a traffic lane or avoiding a temporary roadwork), a driver could overtake the shuttle.*

The three signalized intersections are located on a 170 m long section of Rådhusgata (Fig. 2). These intersections are:

A. Rådhusgata x Nedre Slottsgate
B. Rådhusgata x Kongens gate
C. Rådhusgata x Kirkegata

The signal plans on these intersections are not fixed. They vary according the traffic conditions, with Rådhusgata considered as the main link. In this pilot project, there was no signal from the shuttles to the signal system, therefore there was no prioritization of the shuttles. However, the approaching shuttles were receiving a signal about the status of the traffic lights.

Figure 2 - Studied intersections and the shuttle directions (the map taken from www.finn.no)

There are signalized zebra crossings on all intersections approaches. The speed limit on Rådhusgata is 30 km/h. Along the studied section, Rådhusgata is a one-way street for motorised vehicles (except for the short section between Christiania Torv and Nedre Slottsgate, that has two-way traffic), with the traffic lane being 3.20 m wide. There are red bicycle lanes (1.50 m wide) along both sides of Rådhusgata, allowing cyclists to ride in both directions.

2.2 Video recordings

Three camera units were installed on the three signalised intersections in weeks 35 and 36 in August/September 2020 (27-30/8 and 3-4/9). The cameras' positions, recorded areas and observed maneuvres of the shuttles are shown in Figures 3 and 4. The recordings were conducted from 6m height, with video resolution 720x480 pixels and speed 30 fps.

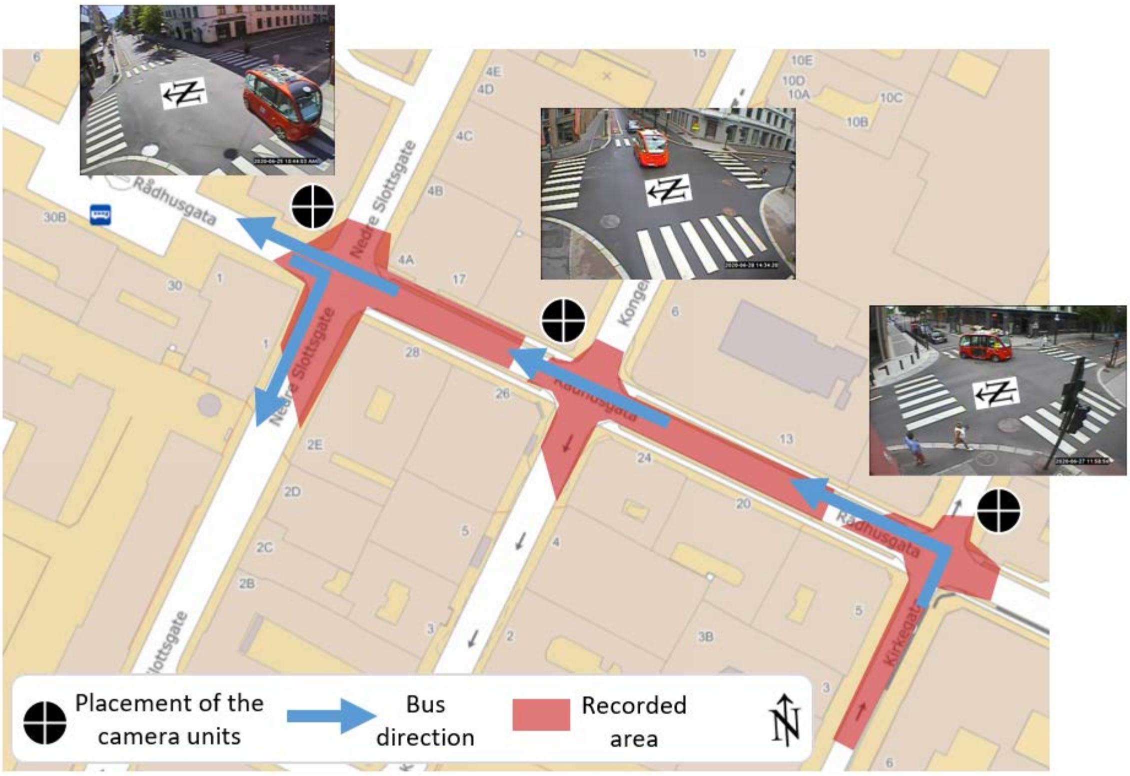

Figure 3 - Positions of the cameras and the view from the cameras, the recorded areas and the maneuvers of the shuttles (blue arrows)

Figure 4 - Placement of the camera units on (from left) Nedre Slottsgate, Kongens gate and Kirkegata

Sixty-three hours of videos were collected on each intersection (i.e. 189 hours in total). The camera #1 covered two different maneuvers, as the shuttle was driving through intersection A twice, in the beginning and end of its route.

2.3 Video analysis

In the first step, it was necessary to identify the shuttles in the video recordings. For this, RUBA "watch-dog" software was applied (Tønning et al., 2017). The presence detectors created in RUBA were set to very benevolent detection parameters, therefore they provided a print screen every time any road user crossed the detector. Print screens containing the shuttle were manually identified in a photo viewer, and based on the time shown on these print screens the relevant sequences from the video recording were cut out into short clips.

Furthermore, every intersection was divided into four zones:

- **Zone #1**: Approach towards the intersection to the stopping line
- **Zone #2**: The first zebra crossing
- **Zone #3**: "Inside" the intersection (between the first and second zebra crossing)
- **Zone #4**: The second zebra crossing and exit from the intersection

These zones were similar for all intersections (see an example on Fig. 5).

Figure 5 – Example of intersection zones

In the next step, the short video clips containing the shuttles were manually viewed in order to collect the set of operational variables (see Table 1 for their list and definitions), separately for each zone. The following terminology was used:

- *Case* – the whole driving maneuver of the shuttle through the intersection
- *Situation* – any event when the shuttle behaved in strange, odd or unexpected way, or had an encounter with other road users (with or without a reaction)
- *Reaction* – the way the shuttle/other road user behaves. In some situations, no reaction can be considered as the reaction as well. The reaction can be correct / incorrect (based on traffic rules) and mild (smooth) / excessive (based on its intensity)
- *VRU* – vulnerable road user (cyclist, e-scooterist, pedestrian)

Table 1 - Operational variables

Variable	Description
Reaction time to the traffic signals [seconds]	The reaction time of the stopped shuttle to the change of the signal from red to green. Measured from the moment when the green signal appeared to the initial movement of the shuttle (detected visually). The time was measured in SM Player. Because of limited visibility, the measurements were not possible on Intersection A1 (Nedre Slottsgate, direction from Christiania T.) and Intersection B (Kongens gate).
Signal phase on the approach	Signal phase in the moment when the shuttle was approaching the intersection – ca 5-10m in front of the stopping line (Green; Red, Change from green to red; Change from red to green)
Position on the stopping line	The position of the shuttle on the stopping line, when standing on the red signal. Two dimensions were considered: ▪ Longitudinal: shuttle's distance from the stopping line ▪ Traverse: shuttle's position in the traffic lane (right, centre, left)
Description of the shuttle behaviour (in every zone)	Brief description, focusing on the shuttle interactions with other road users, untypical behaviour, reactions, compliance with traffic rules, type of road users involved etc.
Context level[3]	In order to estimate the complexity of the situation, four context levels were recognized: ▪ *Level 0 – simple*: only the shuttle is on the scene ▪ *Level 1 – single*: there is a single road user in the proximity (ahead or beside) of the shuttle. The road user behaves according to the traffic rules ▪ *Level 2 – complicated*: there are several road users in the proximity of the shuttle. They behave according to the traffic rules ▪ *Level 3 – complex*: at least one road user in the proximity of the shuttle that behaves unpredictable (e.g. somebody walking on red light)
Safety level	In order to estimate the safety of the situation, three levels of safety were considered: ▪ *Level 1 – smooth*: according the traffic rules, safe, nothing occurred ▪ *Level 2 – not smooth*: untypical/unexpected behaviour, confusion, slight evasive manoeuvres without any obvious reason ▪ *Level 3 – critical/unsafe/:* conflict, almost an accident
Contributory factors	The factor(s) that might have contributed to the reaction / behaviour of a shuttle in a situation

Based on the collected operational variables, it was possible to recognize untypical/odd situations and correct/incorrect reactions of the shuttle and estimate the potential risks, particularly in relation to the traffic signal operation.

The Result chapter provides the findings separately for each intersection's zone, while the Discussion chapter summarizes all the findings in more comprehensive way.

[3] *Inspired by the Cynefin model of complexity, which consists of the five properties (contexts): obvious – complicated – complex – chaos – disorder (Fierro & Putino, 2010)*

3 Results

3.1 Intersection A – Rådhusgata x Nedre Slottsgate

The shuttle drove through this intersection twice: from Christiania Torv turning right to Nedre Slottsgate (manoeuvre A1) and straight along Rådhusgata towards Christiania Torv (manoeuvre A2). Therefore, these two manoeuvres are analysed separately.

3.1.1 Manoeuvre A1 - Right turn to Nedre Slottsgate

There were in total 106 right-turning shuttles recorded in Nedre Slottsgate. As can be seen from Figure 6, the camera did not cover zone #1 (approach along Rådhusgata from Christiania Torv) and a part of zone #2 (part of zebra crossing on Rådhusgata). The signal phase was recognizable from the traffic light in the upper left corner of the recording. However, the stopping line on the approach was not visible and therefore it was not possible to measure the reaction time of the shuttle on the traffic signal change.

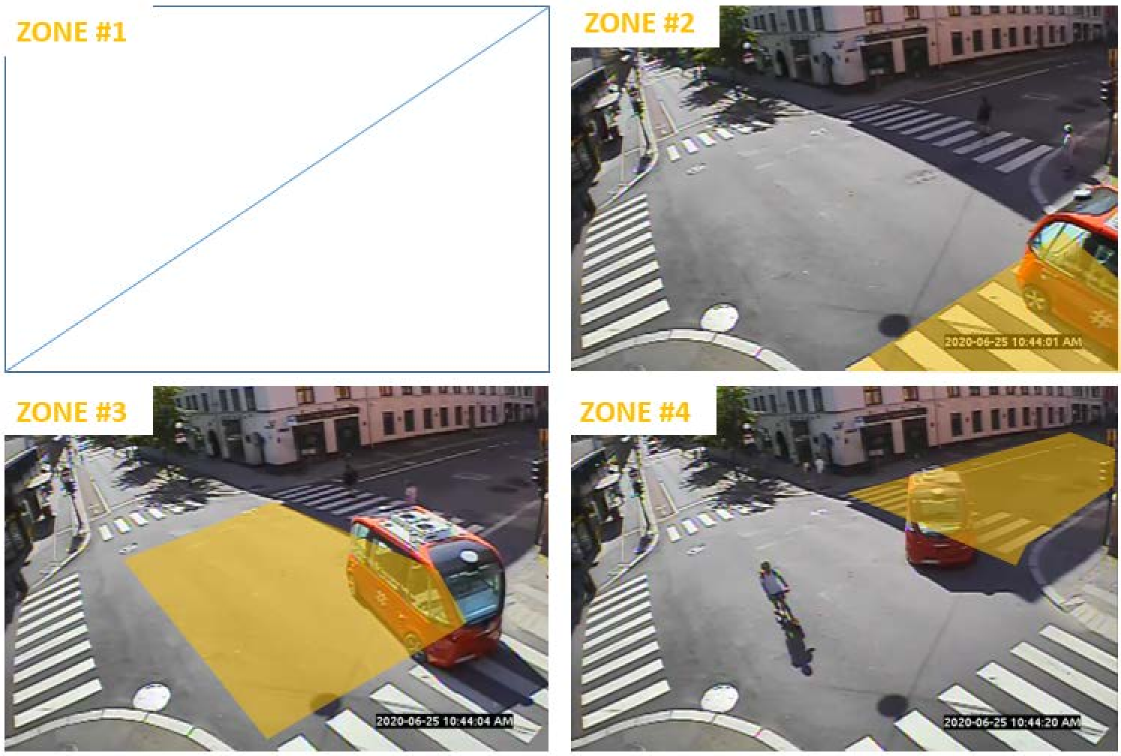

Figure 6 - Three visible zones at the intersection A1

In 49 of the cases, the manoeuvre of the shuttle was smooth and the bus did not experience any encounters. In the remaining 57 cases, there were 70 situations detected.

Zone 2 (19 situations)

There were three types on situations recognised:

1. *A road user was overtaking the shuttle from left (n=10)*

There were several situations, when the other road users were overtaking the shuttle from the left, over the zebra crossing. In those situations, the shuttle does not need to react. However, in three situations the shuttle reacted - in two encounters with VRUs the shuttle slightly slowed down, while the overtaking car (that was later turning left) caused the shuttle to stop hard (27/8, 10:20 - see Fig. 7). After that hard stop the shuttle driver probably overtook the driving to continue.

Figure 7 - A car overtaking the shuttle, that stopped hard as a reaction to this maneuver

2. *The shuttle reacting to crossing pedestrians (n=8)*

In Zone 2, the shuttle has already reacted to the pedestrians, that were crossing the zebra crossing across Nedre Slottsgate (Zone 4), either from the left or right (from the shuttle perspective). Seven of these situations were observed. In five of them, the shuttle reacted correctly (slowing down to provide enough time/space to pedestrians). In one situation, the shuttle stopped too hard (pedestrian from the right) and after that stop the shuttle driver probably overtook the driving (30/8, 15:09). In another situation, both the shuttle and a pedestrian (approaching the crossing from right) stopped, and the shuttle drove first, as the pedestrian did not show the willingness to continue. The pedestrian waited and crossed after (29/8, 14:53).

Only one situation was observed with a pedestrian on the zebra crossing across Rådhusgata. Here, the pedestrian was pretending to enter the crossing on the red signal, just in front of the approaching shuttle. It was obviously the intention of the pedestrian to test the shuttle's reaction – the shuttle correctly stopped (28/8, 19:21).

3. *Other (n=1)*

In this situation, a car in front of the shuttle was turning left, the shuttle correctly detected it and slowed down (29/8, 15:35).

Zone 3 (35 situations)

There were two types of situations in Zone 3 – first one with pedestrians on the zebra crossing across Nedre Slottsgate, and second one with different encounters inside the intersection.

1. *The shuttle reacting to pedestrians crossing Nedre Slottsgate (n=31)*

There were 31 situations observed when the shuttle was encountering pedestrians that were crossing/starting to cross the zebra crossing across Nedre Slottsgate. The shuttle had two options here - to give way to pedestrians or not.

In 18 situations, the shuttle gave way. Twelve of these situations went smooth, the shuttle reacted correctly (slowing down, giving way). In five situations, the shuttle reaction was correct, but slightly excessive, such as breaking too hard or stopping too long. In the last situation the reaction of the shuttle was not correct – it stopped, despite the fact that the pedestrian had already crossed, was standing on the sidewalk near the crossing (28/8, 19:21).

In 13 situations, the shuttle did not give way to pedestrians. In four of them, the intentions of the pedestrians were not clear. Therefore the shuttle slowed down, and then drove first. In four other situations, pedestrians were too far from the crossing. In all these situations the reaction of the shuttle was correct and it drove first. The last five cases where the shuttle did not give way were probably due to the fact that the signals were changing at that exact moment probably because the signals were changing at the time of decision (28/8, 17:12; 29/8, 16:14 and 16:46; 30/8, 19:04) or the pedestrian started crossing outside the zebra crossing (28/8, 17:59 – Fig 8). These situations might be considered incorrect reactions.

Figure 8 –Pedestrians (in red circle) starting to cross slightly outside the zebra crossing, the shuttle drives first

2. *Other (n=4)*

In one situation, the shuttle stopped because there were two cyclists approaching from the left, from Nedre Slottsgate, not stopping for the red signal. The correct reaction would probably have been to continue driving (29/8, 12:40 – Fig. 9).

In another situation, the shuttle correctly did not react on a cyclist that was riding across the intersection (27/8, 16:59). In the third situation, the shuttle entered the intersection when the signal was changing and speeded up to leave the intersection (27/8, 18:59). In this last situation, the shuttle correctly didn't react to the pedestrians that were crossing diagonally on the red signal behind the shuttle (29/8, 17:30).

Figure 9 – Here, the shuttle had to deal with pedestrians crossing the zebra on green light, at the same time as cyclists approached from the left on red signal.

Zone 4 (n=16)

There were two types of situations recognized:

1. *The shuttle stops/slows down without any reason (n=11)*

In these situations, the shuttle stopped after the zebra crossing (n=10) or on the zebra crossing (n=1), without an obvious reason. In several situations, we observed some kind of correction trajectory manoeuver by the shuttle before it stopped. This might be because there was a delivery truck/car ahead blocking the road, but this was not visible from the camera so we don't know the reason.

2. *Encounters with other road users (n=5)*

These was a variety of encounters with other road users, involving risky maneuvers from the other road users, such as a van overtaking the shuttle from the left (4/9, 11:13); a scooter overtaking the turning shuttle from the right (28/8, 15:12 – Fig. 10); cyclists approaching from left from Nedre Slottsgate on red signal and trying to overtake the shuttle (29/8, 12:40); or a car driving in Nedre Slottsgate in the opposite direction (27/8, 11:43). The shuttle acted correctly in all these situations – it changed the speed or did not react.

Figure 10 – A scooter overtaking the turning shuttle from its inner side in Zone 4

3.1.2 Manoeuvre A2 - Along Rådhusgata towards Christiania Torv

In total there were 102 straight going buses recorded in the route along Rådhusgata towards Christiania Torv. There were in total 35 situations detected in A2. Most of them were observed in zone #1.

As can be seen from Figure 11, the camera did not fully cover zone #4 (exit from the intersection). The signal phase was recognizable from the traffic light in the upper left corner of the recording.

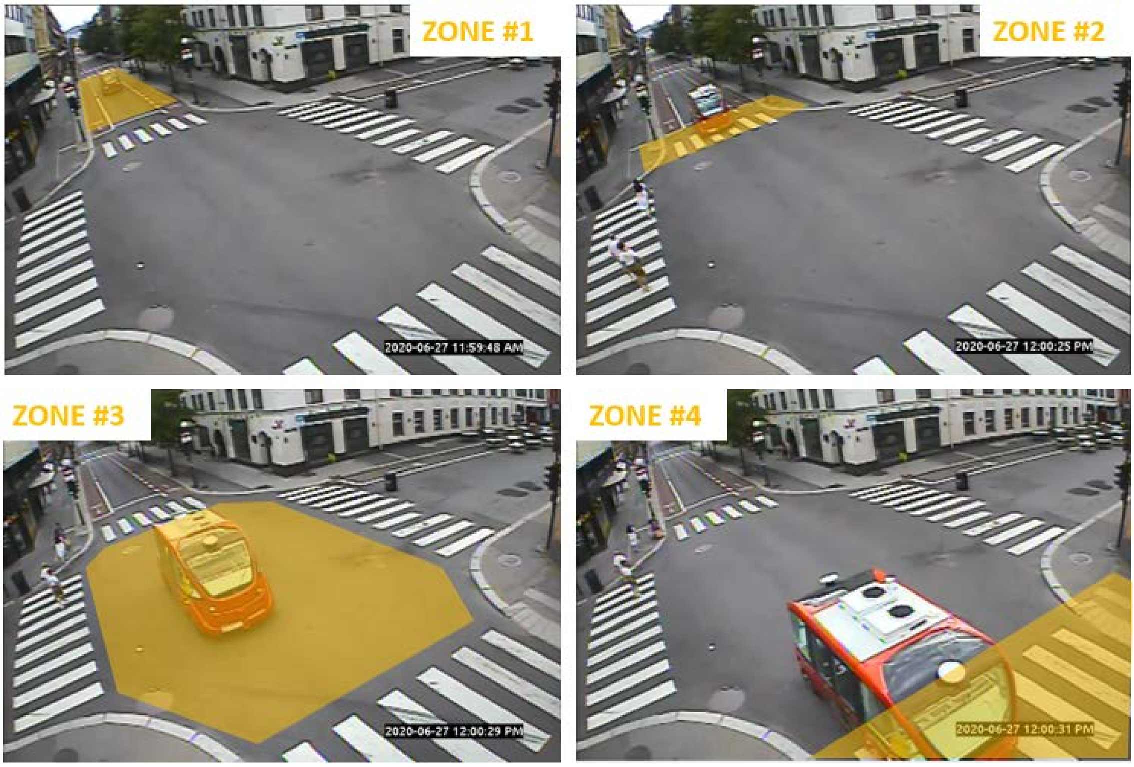

Figure 11 - Four zones at the intersection A2.

The typical stopping position of the shuttle on the red signal was in the middle of the traffic lane, very close to the stopping line. On several occasions we observed that when both cyclist(s) and the shuttle were waiting for the green signal next to each other, the cyclists let the bus go first on the green signal. In 28 cases it was possible to measure the reaction of the stopped shuttle on the change of the signal from red to green. The mean reaction time was 5.7 seconds (see Fig. 12 for more details).

Mean	**5,7s**
Median	**3,8s**
SD	**3,9s**
Min	**2,3s**
Max	**17,0s**

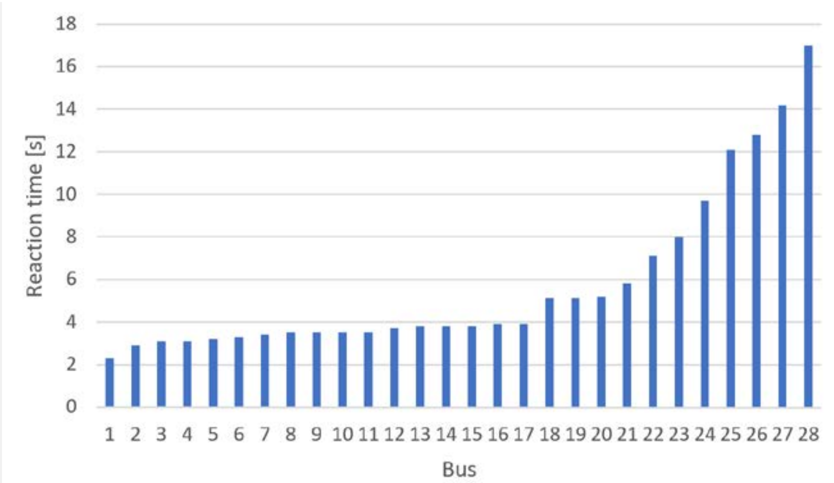

Figure 12 - The shuttle's reaction times on green signal

The reaction times (>8 s) were very long on several occasions. There might be a connection between reaction time and a hard stop by the shuttle that occurred earlier on the approach.

Zone 1 (26 situations)

The situations in Zone 1 were characterized by either strange stopping behavior (hard or sudden, unexpected stops) or inconsistent speed on the approach to the intersection. In 19 of these situations, there was a cyclist or an e-scooterist in the bicycle lane in proximity of the shuttle, and/or there was a change of signal (from green to red, n=8). In 7 situations, it was not possible to identify any contributory factor for the shuttle's reaction. Several stops occurred relatively far from the intersection (10-15m before of the stopping line). Consequently, after some of these stops, the shuttle reacted slowly on the change of signal from red to green. In one case the shuttle almost drove on red light – in the moment of the signal change the shuttle hesitated, slowed down, but entered the intersection on late orange phase and continued further (3/9, 12:07).

Zone 2 (4 situations)

The four situations in Zone 2 were characterized with slight avoidance maneuvers of the shuttle or with a sudden stop. First avoidance maneuver occurred without any reason (28/8, 11:42), the second one was correct because of a car approaching in the opposite direction (27/8, 18:57). Regarding the sudden stops, the first one was correct because of an unclear intention of a nearby pedestrian (28/8, 15:08), while the second one was an unnecessary reaction to a cyclist overtaking the shuttle (29/8, 13:48).

Zone 3 (4 situations)

There were four different situations observed in Zone 3. The first one could be characterized as a slight conflict (identified by an evasive action of a cyclist):A cyclist, who rode in the same direction as the shuttle, tried to overtake the shuttle from the right, but had to stop because the shuttle correctly did not react /did not slow down to let the cyclist go first. (28/8, 13:20 – see Fig. 13).

Figure 13 - The conflict situation in Zone 3

In the second situation, the shuttle suddenly almost stopped in the middle of the intersection, probably as a late reaction on a cyclist that overtook the shuttle earlier in zone 1-2 (29/8, 15:30). In the last two situations, the shuttle correctly slowed down to solve the situation – pedestrians crossing on a red signal (27/8, 15:34), and a truck turning left in front of the shuttle (4/9, 12:08).

Zone 4 (1 situation)

There was only one situation observed in Zone 4, when a motorcycle decided to overtake the shuttle over the zebra crossing. The shuttle did not react to that risky behavior (Fig. 14).

Figure 14 - Motorcycle overtaking the shuttle over the zebra crossing in Zone 4

3.2 Intersection B – Rådhusgata x Kongens gate

In the Rådhusgate/Kongens gate intersection, a total of 104 shuttles were recorded. As mentioned previously, the signal phase on the approach was not recognizable from the video. Therefore, it was not possible to measure the shuttle's reaction time on traffic signal change. The stopping positions of the shuttle on red signal were consistent. The shuttle typically stopped in the middle of the traffic lane, very close/tight to the stopping line.

Figure 15 - Four zones at the intersection B

There were 12 situations identified, the majority of them occurring in zone #1.

Zone 1 (11 situations)

The situations in Zone 1 were characterized by different types of stops or slow reactions. There was a hard stop at the stopping line. probably as a reaction to signal change (28/8, 19:40); a slow start when the shuttle was waiting on red signal behind another car (e.g. 4/9, 11:07); a sudden stop without any visible reason (28/8, 18:42); an unnecessary stop because of a parked truck alongside of the street (28/8, 10:09); a "too early stop" as a reaction to a pedestrian crossing on green light (27/8, 12:32); a strange trajectory during the approaching maneuver, with no obvious reason (28/8 - 13:48, 14:50).

Zone 2 (1 situation)

In the one detected situation in zone 2, the shuttle stopped as a reaction to an e-scooterist who was coming from the right on a red light (30/8, 16:53 – see Fig. 16). The shuttle's reaction occurred in the zone 2, even if the el-scooterist was riding far away in zone 3. The reaction was more "preventive" than necessary, there was no obvious risk.

Figure 16 - El-scooterist entering Zone 3 on a red signal triggered the shuttle to stop (the reaction occurred in the position captured on the photo).

3.3 Intersection C – Rådhusgata x Kirkegata

At the intersection Rådhusgata/Kirkegata, the shuttle turns left from Kirkegata into Rådhusgata. A total of 96 shuttles were recorded.

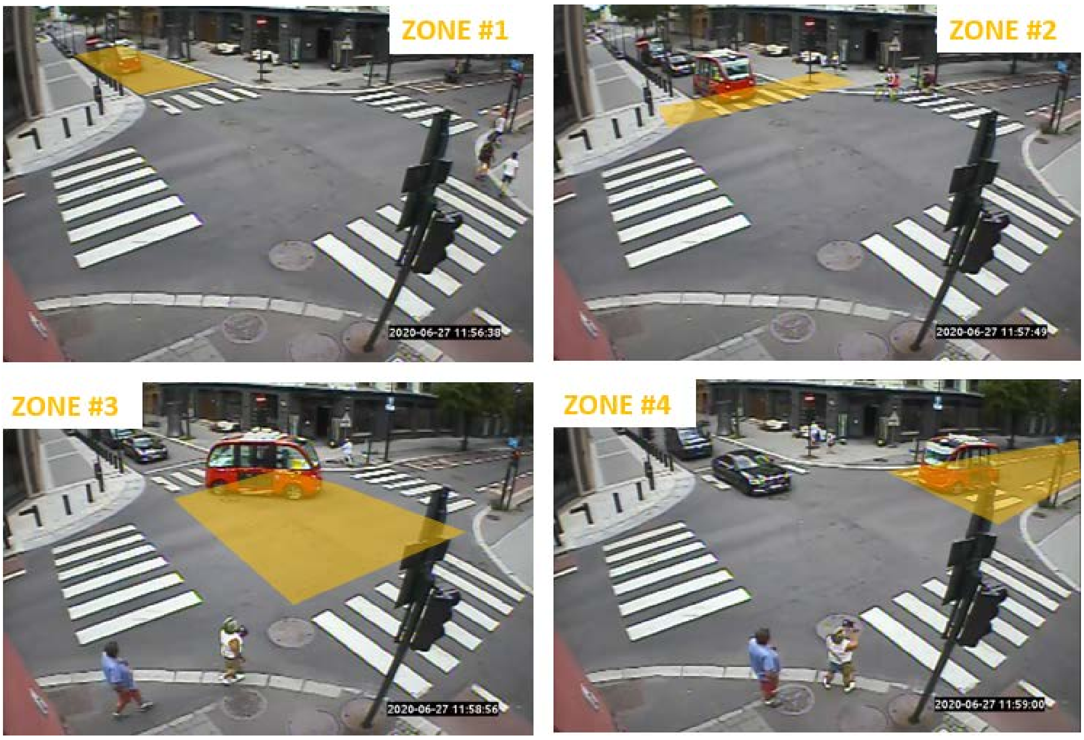

Figure 17 - Four zones at the intersection C

In 33 cases, the shuttle had a green signal, in 42 cases a red signal and in 24 cases there was a signal change (from green to red – 9x, from red to green – 19x). In the situations with the red signal, all the shuttles stopped on the right side of the street, just at the stopping line. The mean reaction time of the shuttle that was stopped on a red signal when the light turned green, was 4,4s. The reaction time was consistent, with only small standard deviation (see Fig. 18 for more details). There were a few excessively long reaction times, which may be connected with the behaviour of nearby pedestrians or with a hard stop on the approach.

Mean	**4,4s**
Median	**4,3s**
SD	**1,8s**
Min	**0,0s**
Max	**12,0s**

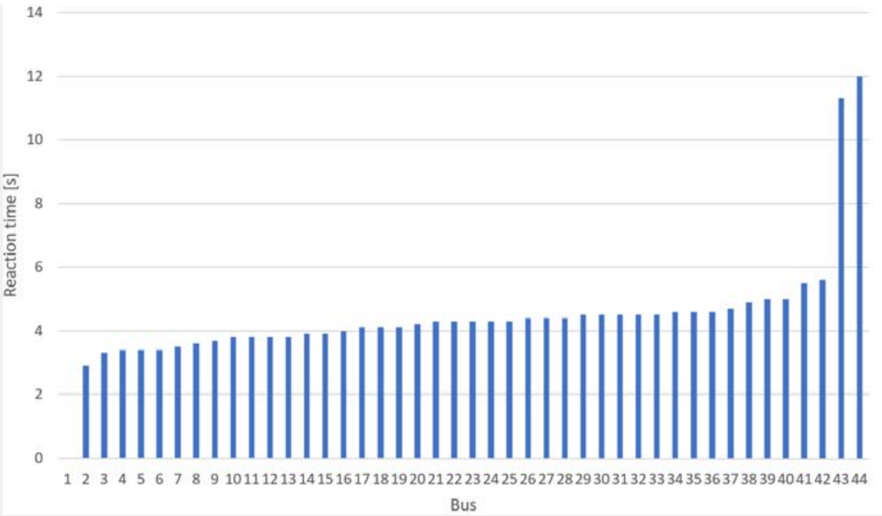

Figure 18 - The reaction times on green signal

51 cases went smoothly, without any problematic situations. In the remaining 45 cases, 52 situations were detected, most of them in Zone 3.

Zone 1 (20 situations)

Three types of situations were recognized:

1. *Unnecessary reactions further back from the intersection (n=4)*

Four situations were observed 10–50m from the stopping line, when the shuttle was reacting to cars that were parked along the left side (from the shuttle's perspective) of the street. In all these situations, the shuttle made an unnecessary stop and at least twice it seemed that the shuttle driver had to take over the driving, so the shuttle could continue.

2. *Close to the intersection - correct reactions to other road users (n=5)*

In four instances, the shuttle correctly reacted (slowing down or stopping) to risky or unexpected behaviour of other road users (such as pedestrian walking on red light – 28/8, 16:08; 29/8, 12:32; 13:02; a car overtaking from the left – 30/8, 17:51 – Fig. 19; and an e-scooterist riding towards the bus 30/8, 14:32).

Figure 19 - The car overtaking the shuttle from the left in Zone 1-2

3. *Close to the intersection - Incorrect reactions to other road users (n=11)*

In the remaining 11 situations the shuttle did not react correctly. Ten of these situations occurred when there was a change of the traffic signal (7x from red to green). The reactions of the shuttle were different types of stops (hard, sudden, short, long stops), or inconsistent speed. In three situations, the behaviour of vulnerable road users might have contributed to the shuttle's impropriate reaction. In the rest of the cases the reaction of the shuttle was triggered by signal change.

Zone 2 (3 situations)

There were three situations observed in Zone 2. In two of them, the shuttle's reaction was not correct – a delayed hard stop, probably as a reaction to an e-scooterist overtaking from the left (28/8, 17:53), and a hard stop without any obvious reason (30/8, 12:09). In the third situation the shuttle reacted correctly, as it stopped when several e-scooterists rode towards the shuttle (29/8, 14:42).

Zone 3 (26 situations)

In Zone 3 the shuttle reacted to vulnerable road users who were in different positions (such as pedestrians crossing the zebra crossing, cyclists waiting on the traffic light on the approach from Rådhusgata, or pedestrian on the sidewalk).

1. *Correct reaction to VRUs (n=15)*

In 15 situations, the shuttle correctly reacted on the behavior of other road users (mostly pedestrians on the zebra crossing across Rådhusgata). The shuttle slowed down/stopped in order to give way. In 11 of these situations, the shuttle continued after the encounter without any problem. However, in four situations, the reaction was too long timewise or too intensive. In all of these situations the shuttle driver had to take over the driving, in order to move the shuttle from the intersection.

2. *Incorrect reaction to VRU (n=11)*

In 11 situations, the shuttle's reactions to other road users were not correct. The shuttle typically stopped in the middle of its left-turning manoeuver, because there were either a pedestrian standing nearby the crossing, a pedestrian who had already crossed, or there were cyclists waiting on the approach (in direction from Christiania Torv), placed inside the intersections (Fig. 20). These stops resulted in situations where the shuttle stayed "locked" inside the intersection even after the change of signals (in one case for 2:30 min – 4/9, 11:37) causing the other road users to drive around the shuttle (Fig. 21). Typically, the shuttle driver had to take over the driving and move the shuttle out of the intersection.

Figure 20 - The positions of the waiting cyclists, that triggered several reactions by the shuttle in Zone 3

Figure 21 - The shuttle stayed inside the intersection after an unnecessary stop in Zone 3

Zone 4 (4 situations)

In all four situations, the shuttle correctly reacted to the behaviour of cyclists or pedestrians. In one situation it stopped (probably too hard) because a cyclist in the opposite direction was overtaking another cyclist in the bicycle lane (27/8, 14:48). In the second, it performed an avoidance manoeuver around a group of cyclists (28/8, 10:09), and in the remaining two situations it correctly drove first across the crossing because the pedestrians were too far away.

4 Summary of results

In total, 408 shuttles were detected in the video recordings. 170 situations were identified, where the shuttle reacted or had an encounter with other road users. Table 2 provides the overview of the number of situations detected for every zone and intersection.

Table 2 – Number of situations for each zone and intersection

	A1 (right turn)	A2 (straight)	B (straight)	C (left turn)	Total
Zone 1	n.a.	26	11	20	57
Zone 2	19	4	1	3	27
Zone 3	35	4	0	26	65
Zone 4	16	1	0	4	21
Total	70	35	12	53	170

Most of the situations were observed in Zones 1 and 3, while Zones 2 and 4 had the lowest number of situations. Turning maneuvers of the shuttle (intersections A1 and C) were characterized by more situations than simpler straight maneuvers (intersections A2 and B). The findings are summarized separately for each Zone below. The shuttle reactions to traffic signals and the shuttle safety are discussed separately in more details.

4.1 Zone #1 (approach to the intersection)

The situations (particularly different types of the shuttle's stops) were observed either along the approach (up to 50m from the stopping line), or in the proximity of the stopping line. The situations, that were observed further away from the intersection, were characterized by a strange stopping behavior (such as hard, sudden unexpected stops) or inconsistent speed and a strange trajectory. In many of these situations, the reaction of the shuttle had no obvious reason. Some of the stops were a reaction to cars that were parked along the left side (from the shuttle's perspective) of the street. In these situations, the shuttle had sufficient (but constrained) space to pass these cars, but the shuttle stopped instead. It seemed that the shuttle driver had to take over the driving in some of these situations. Furthermore, in several situations the shuttle incorrectly stopped to a VRU riding in the bicycle lane.

Closer to the intersection, the contributory factors for unexpected stops or odd behavior were changing traffic signals, sometimes combined with an unclear/unexpected behaviour of a nearby VRU.

4.2 Zone #2 (first zebra crossing)

Most of the situations were observed in intersection A1, where the shuttle was turning right. In this intersection, the shuttle in Zone 2 reacted to pedestrians crossing in Zone 4 and most of the reactions were correct. Incorrect reactions were triggered by untypical situations, such as pedestrians crossing slightly outside the zebra crossing or pedestrians standing near the crossing. Furthermore, other road users were often overtaking the shuttle (that was slowing down to turn right) from the left, over the zebra crossing. In several cases, the shuttle incorrectly reacted to those manoeuvers.

4.3 Zone #3 (inside the intersection)

Almost all situations were observed in the two intersections, where the shuttle was making a turning maneuver (left or right). In intersection C, 11 situations were observed when the shuttle stopped in the middle of its left-turning maneuver. These unnecessary stops were triggered by either a pedestrian standing near the crossing, a pedestrian that had already crossed or there were cyclists waiting on the approach (in direction from Christiania Torv), placed in an untypical position. This might suggest some issue with the detection in the left front area of the shuttle. These incorrect stops resulted in situations when the shuttle stayed "locked" inside the intersection even after the change of signal, creating an obstacle to other road users. Typically, the shuttle driver had to take over the driving and move the shuttle out of the intersection.

Furthermore, in several situations the shuttle did not give way to pedestrians crossing the zebra crossing (Zone 4). Most likely this was caused by a change in the traffic signal or by a pedestrian who was crossing slightly outside marked zebra crossing.

4.4 Zone #4 (second zebra crossing, exit)

There were no issues identified in the Zone 4, except for the intersection A1. The shuttle stopped several times in this spot without any obvious reason. However, as the camera did not cover the section of the street ahead of the shuttle, it might be that the shuttle correctly reacted to for example a delivery truck parked there.

4.5 Reactions on traffic signal change

Due to the different camera angles and variable light conditions, the traffic signals were recognizable only at the intersections A2 and C. Therefore, the findings are relevant for these intersections only.

It was possible to notice the shuttle adjusting its speed on the approaches depending on the signal phase. When the signal was red, it slowed down (to avoid the stop). When the signal was green, the shuttle sometimes increased the speed in order to catch the green. This might suggest good functionality of V2X communication if the shuttle is approaching the intersection in the middle of the signal phase. However, the situations when the shuttle encountered the change of traffic phase (particularly from green to red) closer to the stopping line, were often characterized by incorrect reactions of the shuttle. This was even more evident in situations when such change occurred simultaneously with another untypical/unexpected situation (e.g. a pedestrian trying to cross). In some of these combined situations, the shuttle stopped hard slightly inside the intersection, the signal changed to red, and the shuttle reversed back. In several cases the shuttle driver had to take over the driving to solve the situation.

The reaction time on the change to a green signal were visibly slower compared to that of "ordinary" personal cars. The typical reaction time on a green light when the shuttle was standing on the red light as the first vehicle was about 4-5 seconds. However, there were several very long reaction times observed (>10s). These long reaction times might be caused by behaviour of nearby pedestrians or by a previous hard stop of the shuttle.

In situations when the shuttle was waiting for a green signal behind another car, it also reacted relatively slow after the car ahead started to drive.

Furthermore, we observed several times, that when both cyclist(s) and the shuttle were waiting for a green signal next to each other on the stopping line, the cyclists let the shuttle go first when the signal turned green.

In situations when the shuttle incorrectly stopped in the middle of the intersection (particularly relevant for the intersection C), and the signal changed to red, the shuttle "froze" and blocked the area. In these situations, the shuttle driver had to take over the driving to solve them.

4.6 Safety

The shuttle has its typical low-speed and defensive style of driving. The reactions of the shuttle were correct in most of the encounters. In addition, it correctly recognized several traffic rule violations from other road users and responded accordingly, even within a complex context. There were no severe conflicts observed in any of the analyzed situation.

However, there were circumstances when the shuttle reacted incorrectly (especially with hard, long, unexpected stops). These reactions might increase the risk for other road users. Examples of such circumstances were:

- The change of traffic signal from green to red combined with an unpredictable behavior of other road users or some other untypical situation
- Cyclists standing near the shuttle in untypical positions (especially when the shuttle was turning left)
- Cars parked alongside the street
- Fast road users overtaking the shuttle
- VRU riding close and fast to the shuttle

Furthermore, there were several situations, when the shuttle reacted unexpectedly or excessively without any obvious reason. These incorrect reactions, particularly hard stops on the approach to the intersections (with cars behind the shuttle), might result in rear-end conflicts/collisions and are also unpleasant or even dangerous for passengers inside the bus.

Moreover, there were situations, when the shuttle almost "froze" inside the intersection, particularly after experiencing an incorrect hard/long stop. This created chaotic situations, especially when the traffic signal changed and road users from other directions started to enter the intersection. In these situations, the shuttle driver had to take over the driving.

Regarding the reactions of the shuttle to pedestrians crossing the zebra crossings on green signal, the bus was correctly evaluating the basic/simple situations. However, a strange, unexpected or unpredictable behavior (such as a pedestrian entering the zebra crossing slightly outside the zebra marking or a pedestrian standing nearby after finished crossing) might have triggered an incorrect reaction of the shuttle. The situations when there was a red signal for pedestrians were not problematic for the shuttle.

In addition, the defensive driving style and sensitive and sometimes unpredictable behavior of the shuttles was affecting the behavior of some road users. They were willing to engage in potentially risky maneuvers (e.g. overtaking the shuttle in the intersection) in order to place themselves in front of the shuttle.

5 Conclusion

In the presented study, we used external video recordings to study the performance of the shuttles when driving through three signalized intersections under real traffic conditions. We evaluated the shuttle reactions to the traffic signals and observed their encounters with other road users. This is a type of approach that has not been applied in connection with other shuttle pilots in Europe.

We identified several behavioral patterns and untypical reactions of the shuttles, both in their communication with the traffic signals and in encounters with other road users. Particularly the combination of the signal phase change (from green to red) and an unexpected behaviour of nearby road users, was challenging for the shuttles, causing long and unexpected stops. To continue driving, the shuttle driver had to take over control in these situations and proceed by manual driving. Furthermore, there were situations, when the shuttle stopped without any obvious reason or as an incorrect reaction to a nearby road user (such as to a car parked in the traffic lane). However, we observed re no severe conflicts, mostly due to the low speeds and the defensive driving style of the shuttles.

The safety evaluation of the encounters was based on visual observations of road users' reactions, such as an obvious change of speed or trajectory. Due to the encounters' characteristics (particularly low speeds) it was not feasible to measure the exact numerical characteristics of the encounters (such as time to collision). The situations, when the shuttle driver took over control, were recognized visually (based on obvious movements in the shuttle cabin), because the data from disengagement reports were not available. Despite these limitations, this study provides a unique insight into the safety and performance of the shuttles under real traffic conditions, when driving through signalized intersections. When interpreting the results, the local conditions and specifics, together with the methodological limitations must be considered.

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