Institute of Transport Economics
Norwegian Centre for Transport Research

Automated shuttles in a residential area

Video observations of interactions with other road users in Ski - Hebekk

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1917/2022

Title:	Automated shuttles in a residential area - Video observations of interactions with other road users in Ski - Hebekk
Tittel:	Selvkjørende busser i boligområde – Videoobservasjoner av interaksjoner med andre trafikanter i Ski - Hebekk
Author:	Petr Pokorny, Torkel Bjørnskau, Ole Aasvik
Date:	12.2022
TØI Report:	1917/2022
Pages:	28
ISSN Electronic:	2535-5104
ISBN Electronic:	978-82-480-1973-2
Project Number:	310173
Funded by:	The Norwegian Research Council
Project:	4931 Autopia
Project Manager:	Torkel Bjørnskau
Quality Manager:	Trine Dale
Research Area:	Safety, Security and Resilience
Keywords:	Automated shuttles, Road safety, Video observation

Summary

Automated shuttles are being tested frequently worldwide. Most such pilots take place in more or less controlled environments or in areas with simple traffic conditions. This report provides results from a unique evaluation of the performance of the shuttles in a more complex urban environment. The operation of the shuttles in the residential area Hebekk in Ski has been investigated using external video observations under real traffic conditions. Among the most concerning findings were low willingness of car drivers to give way to the shuttles at right-hand priority intersections, many inadequate reactions of the shuttles at intersections and the inability to manage the interactions with pedestrians walking along road sides. Such knowledge can be utilized in other pilots with automated vehicles.

Kort 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 boligområdet Ski – Hebekk ble undersøkt ved hjelp av eksterne videoobservasjoner under reelle trafikkforhold. Blant funnene var lav vilje hos bilførere til å vike for bussen i kryss med vikeplikt fra høyre, mange ikke adekvate reaksjoner fra bussene i kryss og manglende evne til å håndtere samhandlingen med fotgjengere som går langs veikantene. Slik kunnskap kan brukes videre i andre forsøk med automatiserte kjøretøy.

Preface

Public transport provider in the Oslo-region RUTER has been testing automated shuttles (SAE Level 3 automation) through several pilots. One of these pilots was deployed in Ski in 2021. The pilot was carried out within the AUTOPIA project (Autonomous Universal Transport Of People In Akershus). AUTOPIA was a two-year project led by RUTER and funded by the Norwegian Research Council as an Innovation project for the public sector. The other involved partners were the Institute of Transport Economics (TØI), the Norwegian Public Roads Administration (NPRA), Viken county and Holo.

One of the objectives of AUTOPIA was to evaluate the interplay between the shuttles and other road users on constrained roads inside a residential area. TØI conducted this evaluation using external video observations. This report summarizes the findings of this evaluation.

At TØI, Petr Pokorny has had the main responsibility for collecting and analyzing data, and for writing the report. Ole Aasvik assisted in data collection and reviewed the report. Torkel Bjørnskau has been the project manager. Trine Dale and Aslak Fyhri have been responsible for the quality assurance of the report, Trude Kvalsvik has prepared the report for publication. The project partners' contact persons have been Lars Gunnar Lundestad, Vibeke Harlem, Helene Otterdal, Silje Andersen Sævig and Eirik Oskari Halvorsen from Ruter, Magnus Larsson, Irina Jonsson and Pål Jødahl from NPRA, Hans Fridberg from Holo and Thomas René Sirland from Viken county.

Oslo, December 2022
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- 193 traffic situations involving the automated shuttle were explored, using external video observations.
- We identified several types of inadequate shuttle’s reactions (such as too “hard”, too long, unnecessary or delayed stops), especially at right-hand priority intersections.
- The inadequate reactions can be attributed to the “defensive” style of the shuttle’s decision making and its strict reactions when there is an object detected within the shuttle’s safety zone/priority area.
- When the shuttle in automated mode encountered a pedestrian walking on the right side of a road section (in the proximity of shuttle’s trajectory), it stopped instead of driving around the pedestrian. Therefore the shuttle drivers were proactively taking control in such situations.
- Regarding the reactions of other road users, our observations indicate that car drivers were more likely to disobey the right-of -way for shuttle than for other cars at right-hand priority intersections.

Transportøkonomisk institutt
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NORSK **Sammendrag**

Selvkjørende busser i et boligområde

Videoobservasjoner av interaksjoner med andre trafikanter i Ski - Hebekk

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- 193 trafikksituasjoner med selvkjørende busser ble analysert ved bruk av eksterne videoobservasjoner.
- Vi observerte flere typer av ikke adekvate reaksjoner fra bussene (som for «harde», for lange eller forsinkede stopp), spesielt i situasjoner i kryss med høyrehånds vikepliktsregel.
- Mange av ikke adekvate reaksjonene kan tilskrives den "defensive" stilen til bussen og harde oppbremsinger når det er et objekt innenfor bussenes sikkerhetssone/prioriterte område.
- Da bussen i automatisert modus møtte en fotgjenger som gikk på høyre side av veistrekningen, stoppet den i stedet for å kjøre rundt fotgjengeren. Derfor tok sjåfører proaktivt kontroll i en slik situasjonen.
- Angående reaksjonene til andre trafikanter, viser våre observasjoner at bilførere overholdt sjeldnere vikeplikten for de selvkjørende bussene enn for privatbiler i kryss med vikeplikt fra høyre.

Selvkjørende busser testes over hele verden, også i Norge. De fleste piloter med selvkjørende busser foregår i avgrensede og kontrollerte områder eller i områder med enkle trafikk¬forhold. I dette prosjektet er de selvkjørende bussene satt ut i reell trafikk i et vanlig boligområde.

Denne rapporten gir en unik evaluering av interaksjoner mellom selvkjørende busser og andre trafikanter under mer komplekse forhold. Slik kunnskap kan brukes videre i andre prosjekter med automatiserte kjøretøy.

Om prosjektet

I perioden januar 2021 til februar 2022 ledet Ruter et testprosjekt av selvkjørende busser i Ski i Nordre Follo kommune.

Den selvkjørende busstjenesten koblet sammen boligområdet Hebekk og sentral-banestasjonen. Lengden på ruten var 4,7 km. og to Toyota Proace minibusser med plass til fire til seks personer pluss sjåfør ble satt i drift i en fast rute i området. Totalt 20 248 kilometer ble kjørt i testperioden. Kjøretøyene var utstyrt med Autonomous Drive System (ADS) teknologi fra Sensible4-selskapet, og kjøreautomatiseringsnivå var nivå 3 i henhold til SAE. Det betyr at det finnes en spesialutdannet sikkerhetssjåfør om bord som kan overta kjøringen hvis en situasjon krever det.

I automatisert modus følger disse kjøretøyene en forhåndsdefinert bane. Dersom bilens sensorer oppdager objekter innenfor sikkerhetssonen deres, reagerer kjøretøyet i henhold til de forhåndsprogrammerte algoritmene - som vanligvis er å stoppe eller bremse farten.

Kjøretøyene opererte i et fast regime (fulgte fast rute med fast rutetabell). I utgangs-punktet ønsket man å teste en on-demand tjeneste, men det ble for komplisert på daværende tidspunkt. Det var imidlertid fortsatt mulig å evaluere mange viktige aspekter ved kjøretøyenes drift, deres ytelse under vintervær, aksept av brukerne og interaksjoner med andre trafikanter. Vi benyttet eksterne videoobservasjoner under prosjektet, og vurderte interaksjoner mellom de selvkjørende kjøretøyene og andre trafikanter langs den delen av traseen som ligger i boligområdet Hebekk. Totalt ble 193 trafikksituasjoner analysert ved bruk av eksterne videoobservasjoner.

Resultater

Resultatene viser flere typer reaksjoner fra bussene som ble betegnet som «ikke-adekvate». For eksempel gjaldt det for «harde», for lange eller forsinkede stopp, spesielt i situasjoner i kryss med høyrehånds vikepliktsregel.

Mange av de såkalte «ikke-adekvate» reaksjonene kan tilskrives den defensive stilen til bussen, og at den utførte harde oppbremsinger når et objekt befinner seg innenfor bussenes sikkerhetssone/prioriterte område.

Da bussen i automatisert modus møtte en fotgjenger som gikk på høyre side av veien, stoppet den i stedet for å kjøre rundt fotgjengeren. Derfor tok sjåføren proaktivt kontroll i en slik situasjonen.

Når det gjelder reaksjonene til andre trafikanter viser våre observasjoner at bilførere overholdt sjeldnere vikeplikten for de selvkjørende bussene enn for privatbiler i kryss med vikeplikt fra høyre.

1 Introduction

1.1 Background

Ski is a municipality center of Nordre Follo municipality with ca 20 000 inhabitants, located about 25 km south of Oslo. The automated shuttle service (line 529) was tested here from January 2021 to February 2022 within the AUTOPIA project.[1] The service connected the residential area Hebekk and the main train station. The route was implemented in two phases (so-called Alpha and Bravo) and its final length was 4,7 km. Figure 1.1 shows the location of the test project and the whole route.

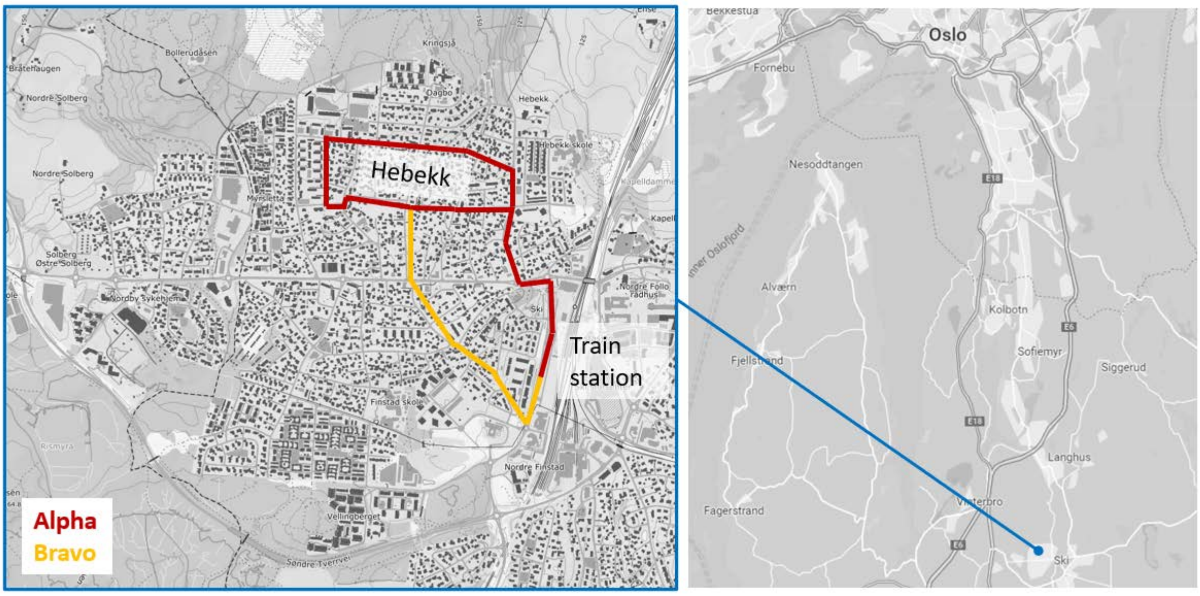


Figure 1.1: Route 529 in Ski.

There were two Toyota Proace vans (hereafter referred to as "shuttles", see Figure 1.2) in service on this route and they drove 20 248 km in total during the project. The shuttles were retrofitted with Autonomous Drive System (ADS) technology from the Sensible4 company. One such shuttle can accommodate 4-6 passengers plus a driver. Their maximum speed was 30 km/h; during the pilot their average speed was 12 km/h (Green et al., 2022). The shuttle's level of driving automation according to SAE[2] was Level 3 (i.e. with a specially trained safety driver on board who can overtake the driving if a situation requires it). In automated mode, these shuttles follow a pre-defined trajectory. If the shuttle's sensors detect anything within their safety zone (a defined space around the shuttle), the shuttle reacts according to the pre-programmed algorithms (typically by stopping or slowing down).

[1] ***AUTOPIA*** *(Autonomous Universal Transport Of People In Akershus) was a two-years Innovation project for the Public Sector funded by the Norwegian Research Council. The project owner was the local public transport authority Ruter.*

[2] *https://www.sae.org/blog/sae-j3016-update*

Figure 1.2: The retrofitted automated Toyota Proace van (photo: TØI).

The overall aim of AUTOPIA was to test the feasibility of a flexible on-demand booking service provided by the shuttles (i.e. the passengers can decide for themselves when and where they want to be picked up and dropped off) and to investigate the potential effect of such service on private car usage in the area. Due to several technological and operational problems (see Green et al. 2022 for more details), it was not possible to implement such on-demand service, and the shuttles operated in a fixed regime (i.e. following the fixed route with a regular timetable). However, it was still possible to evaluate other aspects of the shuttles' operation, such as their performance under winter weather conditions, user acceptance issues and shuttles' interactions with other road users (and vice versa).

This TØI report describes an exploratory assessment of the interactions between the shuttle and other road users along a part of Alpha route located in residential area Hebekk.

1.2 Objectives

The significant part of the route (1,8 km) was located in the residential area Hebekk (red dashed line in Figure 1.3).[3]

[3] *The shuttle was entering Hebekk from a four-arm intersection (Oppegårdveien x Austliveien), where it turned left from Oppegårdveien (Figure 1.3 - bottom right). After this left turn, it drove ca 800 m along Austliveien and Seljeveien and then turned right into Kongleveien. After 260 m it turned right into Nybrottveien, continued along Nybrottveien and after 750 m it exited Hebekk, turning right (give-way traffic sign) into Oppegårdveien (Figure 1.3 - top right).*

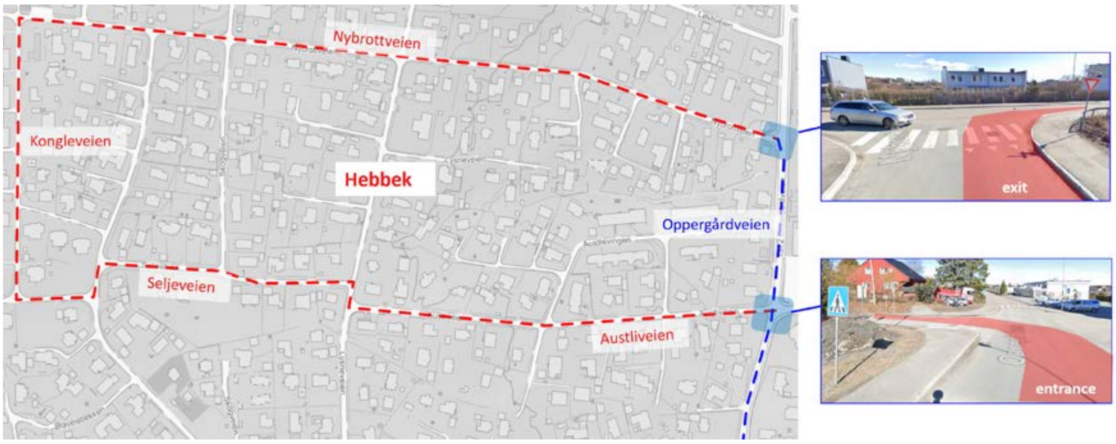


Figure 1.3: Left: the shuttle route – the red line is the fixed route in Hebekk residential area, the blue line presents a part of the fixed route outside Hebekk (the map source: Norgeskart); Right: entrance and exit to/from Hebekk (the street views: Google Maps).

With regards to the traffic regime, Hebekk is established as a 30km/h zone, with right-hand give-way rule on all the intersections inside the zone. There are no traffic signs and road markings in the area. The two-way roads are up to 5.0 m wide and there are no sidewalks along them. Thus, pedestrians and cyclists (often children and elderly) share the roads with motorised traffic (mostly passenger cars, sometimes a large vehicle appears). The motorized traffic volumes are not high. Family houses predominate in Hebekk, with many driveways into the properties. Furthermore, there is lot of greenery (and snow in winter) that might obstruct the drivers' views. Figure 1.4 shows two examples of the traffic in the area.

Figure 1.4: Examples of traffic in Hebekk.

Smooth and safe solutions to traffic situations under such conditions require considerate and attentive driving, and the ability to predict the behaviour of others, often involving communication between drivers and other road users (such as gestures or eye contact).

The aforementioned conditions were expected to be challenging for the shuttle in automated mode. And indeed, during the first days of the service in Hebekk, the shuttle drivers reported that when being in the automated mode, the shuttle was stopping in situations involving a pedestrian walking/standing on the road in the proximity of the shuttle's trajectory. The proper solution in many of these situations would be to slow down and drive around the pedestrian. In order to avoid these unnecessary stops, the shuttle drivers were instructed to proactively take over the driving when they noticed a pedestrian ahead.

In addition to the issue with unnecessary stops due to pedestrians, further safety and operational problems related to the shuttle's interactions with other road users might have been occurring in Hebekk. Therefore, TØI conducted an exploratory observational study, aiming at gaining more detailed knowledge about the shuttle's interactions with other road users. More specifically, we aimed at identifying the common types of interactions, at evaluating the safety of those interactions and at finding examples of behavioral adaptations of other road users, for several types of infrastructure layouts in residential area. This report provides such knowledge.

1.3 Structure of the Report

The structure of the report follows the standard structure of TØI reports. It contains the following chapters: Introduction, Methods and Analyses, Results, Conclusions and Discussions.

The readers have the option of viewing selected videoclips showing the shuttle's interactions by clicking on the hyperlinks (clip #X) in the descriptions of the relevant figures.

2 Method and Analysis

To explore the interactions between the shuttle and other road users, we used a method of external observation with the help of long-term video recordings. Usually, the road users are not aware that they are being recorded, however, in this project, the shuttle drivers knew about the recording. The method consisted of three parts – (1) identification of locations for recording, (2) data collection and (3) data analyses. These are described below.

2.1 Locations of interest

We selected five locations for the observations (Figure 2.1):

- Location #1: Kongleveien x Nybrottveien intersection
- Location #2: Nybrottveien x Lysneveien intersection
- Location #3: Nybrottveien x Oppegårdveien intersection
- Location #4: Austliveien
- Location #5: Austliveien x Lysneveien x Seljeveien intersection

Figure 2.1: Studied locations – the white arrows indicate the direction of the shuttle was driving in (the street views from Google Maps).

Locations #1 and #2 were selected based on the experiences of the shuttle drivers. On these locations, interactions with pedestrians were frequent. On location #3, the shuttle operator wanted to explore how the shuttle drives over the zebra crossing and enter the main road. Locations #4 and #5 were selected based on a heat map, which displays cases (recorded in the period 22/4 – 7/5/2021), in which the shuttle had to stop because of pedestrians walking in its proximity (Figure 2.2).

Figure 2.2: Heat map showing the locations where the shuttle stopped for a pedestrian (period 22/4 – 7/5/2021, source: Holo).

Detailed descriptions of these five locations are provided below.

Location #1 - Nybrottveien x Kongleveien intersection

At this T-intersection, the shuttle was turning right from Kongleveien into Nybrottveien. Right-hand priority rule applies. Under uninfluenced conditions, the shuttle drove through the intersection smoothly, without stopping. Cars often park along the northern side of Nybrottveien.

Location #2 - Nybrottveien x Lysneveien intersection

At this four-armed intersection, the shuttle drove straight along Nybrottveien. Right-hand priority rule applies. Under uninfluenced conditions, the shuttle drove through the intersection smoothly, without stopping.

Location #3 - Nybrottveien x Oppegårdveien intersection

At this T-intersection, the shuttle was exiting the 30 km/h zone and entering the main road (Oppegårdveien). The main road has a 40 km/h speed limit and ADT around 3000 cars in both directions (according vegkart.atlas.vegvesen.no). There is a give-way traffic sign on the approach from Nybrottveien. Here the shuttle was turning right and should yield to vehicles coming from the left on the main road. There

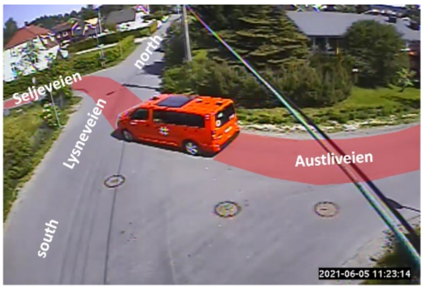
is also a zebra pedestrian crossing across Nybrottveien. Under uninfluenced conditions, the shuttle usually slowly entered the intersection and turned right, without stopping.

Location #4 – Austliveien

Here the shuttle drove straight along Austliveien, in a slight uphill (ca 5%), up to the intersection with Austlisvingen. This intersection is considered as a T-intersection[4] in the analyses. There is a speed hump located in Austliveien. The road on this section is ca. 4,8 m wide. There are several driveways into the residential properties. Under uninfluenced conditions, the shuttle drove along the section and slightly slowed when entering the intersection with Austlisvingen.

Location #5 - Austliveien x Lysneveien x Seljeveien intersection

At this staggered intersection, the shuttle turned right from Austliveien into Lysneveien and after ca. 20 m it turned left into Seljeveien. Right-hand yielding rule applies. Under uninfluenced conditions, the shuttle drove slowly through the intersection. For the analysis, this location was considered as two T-intersections.



2.2 Data collection

To collect the video data, we installed Miovision Scout Camera units at the locations of interest. These cameras record in MP4 format, in 720x480 resolution, with frame rate 30 fps. The cameras have wide dynamic 120° horizontal view, with a digital image stabilizer and they record from the top of the telescopic pole (with max. height of 6 m). Figure 2.3 shows the positions of the camera units and the recording angles.

[4] *It is in fact a 4-armed intersection, however, its fourth arm is just a short, gravel road without any traffic.*

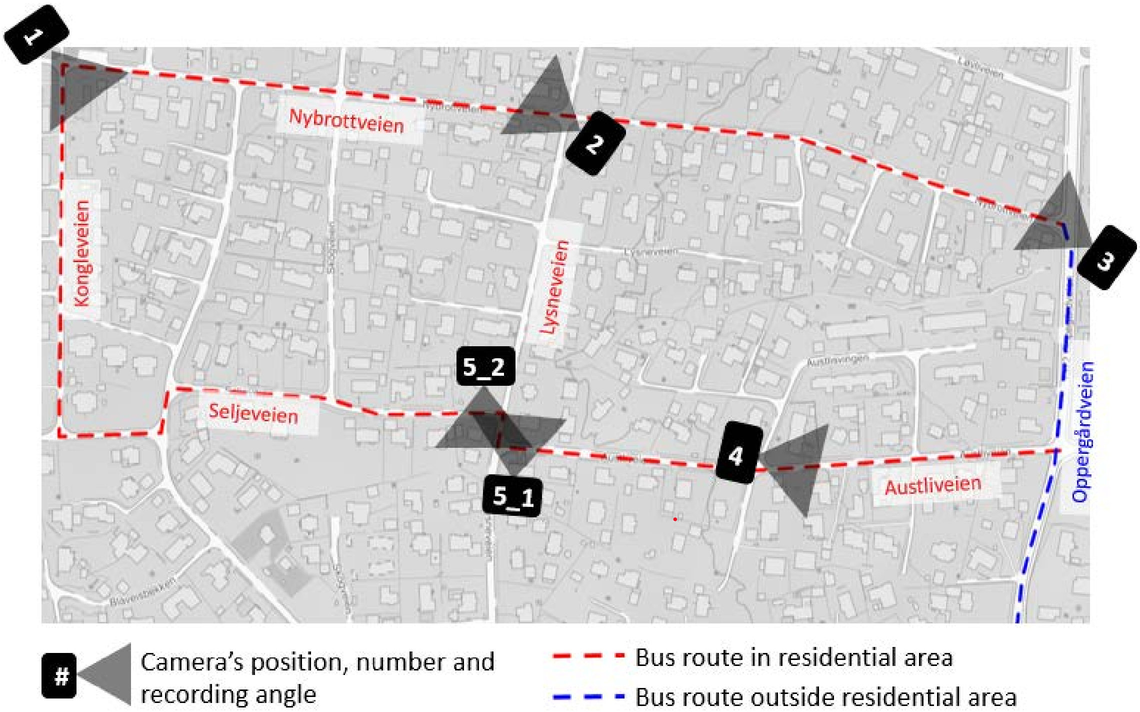


Figure 2.3: Camera units' positions and recording angles.

On location #5 we installed two camera units (5_1 and 5_2) in order to cover both parts of this staggered intersection. Right turn from Austliveien to Lysneveien was recorded by camera 5_1, while the left turn from Lysneveien to Seljeveien was recorded by camera 5_2 (Figure 2.4).

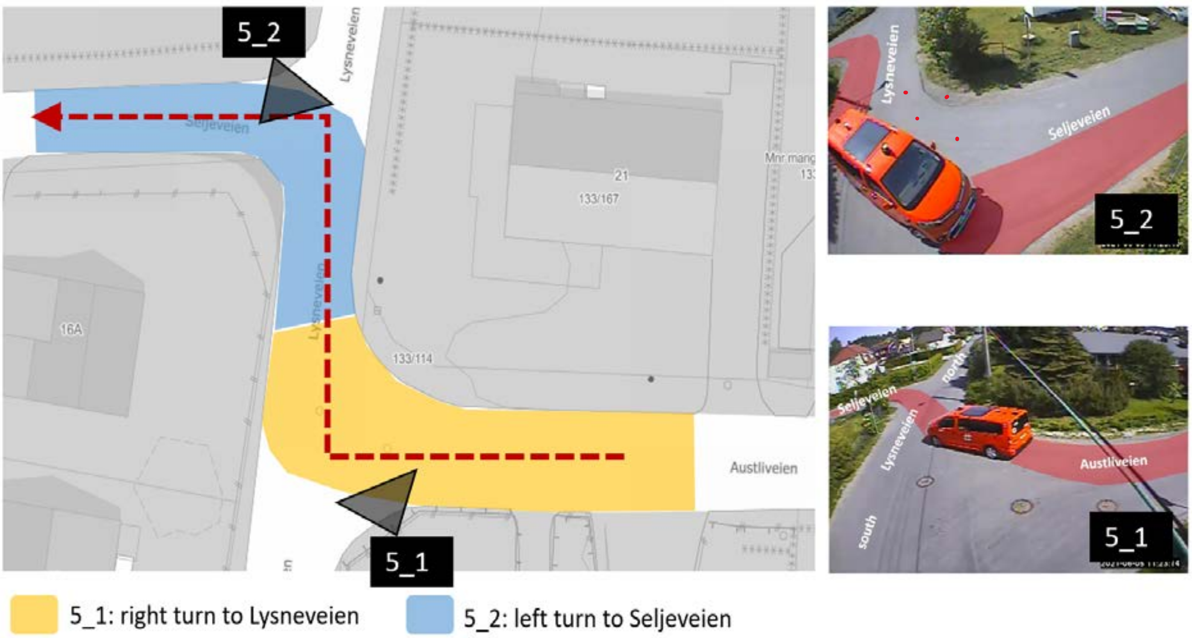


Figure 2.4: Left: Scheme of the staggered intersection (location #5), Right: View from the camera units 5_1 and 5_2.

We conducted the recordings in two seven-days periods, the first in April and the second in June 2021. Locations #1, #2 and #3 were recorded 24/4-30/4/2021, locations #4 and #5 were recorded 5/6-11/6/2021. We set the recording time between 11:00 and 19:00 in order to match the shuttle's schedule.

2.3 Data Analysis

Data analyses consisted of two parts. First, on every location, we detected the shuttle passages in the videos and cut video clips that covered the whole manoeuvre of each passage.

Second, a road safety analyst watched these clips in order to identify the situations in which the shuttle interacted with other road users or performed strangely. These situations were further explored.

2.3.1 Detection of shuttles

To detect the shuttle passages in the video, we used RUBA software[5]. RUBA gives the opportunity to create several types of detectors that detect moving objects in video. For our analysis, we prepared one presence detector for each recording. The positions and shapes of these detectors on all recordings are illustrated as blue rectangles in the pictures in Figure 2.5.

Figure 2.5: Shapes and positions of presence detectors in RUBA.

The detectors had rather benevolent parameters for the occupancy percentage and duration of triggered events, therefore they detected basically everything that at least partially crossed the detector.

RUBA provides the time and the picture of all detected events. We manually selected the detections containing the shuttle (using a generic photo viewer) and consequently cut video clips, that captured the whole manoeuvre of the shuttle (i.e. situation). Clips showing

[5] *The Road User Behaviour Analysis (RUBA) project is a watch-dog tool for computer-based analysis of traffic videos developed by the Visual Analysis and Perception Lab at Aalborg University, Denmark, in collaboration with the Traffic Safety Research Group at Aalborg University (https://bitbucket.org/aauvap/ruba/wiki/Home)*

situations involving other road users or the shuttle performing oddly without anybody/anything nearby were analysed further.

2.3.2 Analyses of selected situations

A road safety analyst viewed the clips and collected a set of the following variables for every situation:

- Type of other road user (*car, motorcycle, van, truck, cyclist, pedestrian, e-scooter*)
- Brief description of the situation
- Location of the interaction *(T-intersection with right-hand priority rule; Four-arm intersection with right-hand priority rule; Road section; T-intersection with traffic sign priority rule*)
- Manoeuvre of the shuttle (*moving pattern/direction of the shuttle, such as "driving straight" or "turning right")*
- Performance/reaction of the shuttle (*such as slowing, stopping, driving around*)
- Intensity of the reaction of the shuttle (*smooth, less hard, hard – estimated visually*)
- Adequacy of the shuttle's reaction (*estimated according the intensity, duration, timing and purpose of the reaction*)
- Compliance with the traffic rules (*for both the shuttle and other road users*)
- Position and moving pattern of another road user (*such as in the intersection, on the exit, on the approach, on the right/left side, moving against the shuttle*)
- Reaction of the other road user (*such as none, moving aside, stopping*)

The following considerations were applied within the analyses:

- Left/right side was considered from the view of the shuttle driver.
- Approach/exit of the intersection was considered according to the shuttle direction.
- If there were several road users presented on the scene and it was not obvious who triggered the reaction of the shuttle, we chose the road user closest to the shuttle as the primary.
- If the shuttle was exiting the intersection (but still was in its turning manoeuvre), and reacted to anybody who was placed on a road section ahead, the position of such interaction was considered to be *on the road section*.
- A combination of a small child on bicycle together with a walking adult was considered as a pedestrian.
- The mode of the shuttles (manual vs. automated) was distinguished visually by observing the shuttle behaviour/style of driving. The automated mode is characterized by a defensive driving style, slower speed, stereotypical trajectory and strict adherence to traffic rules.

Based on the aforementioned variables and assumptions, we categorized the situations and evaluated the interactions. We distinguished between adequate and inadequate reactions (estimated according to the intensity, duration, timing and purpose of the reaction) and their safety in the context of the traffic situation. We did not evaluate the correctness of the shuttle behaviour and performance according to its setting (i.e. a reaction identified by an analyst as "inadequate" might be a correct one according to how the shuttle was programmed). An inadequate reaction does not automatically mean an unsafe or risky reaction. It might be that the shuttle just stopped for a very long time or stopped too early.

3 Results

3.1 Organization of results

We “decomposed” the observed locations into the following single infrastructure layout categories: road section; T-intersection with right-hand priority rule; 4-armed intersection with right-hand priority rule and T-intersection with give-way sign priority (see Figure 3.1 and Table 3.1). The results are organized under these four infrastructure layout categories.

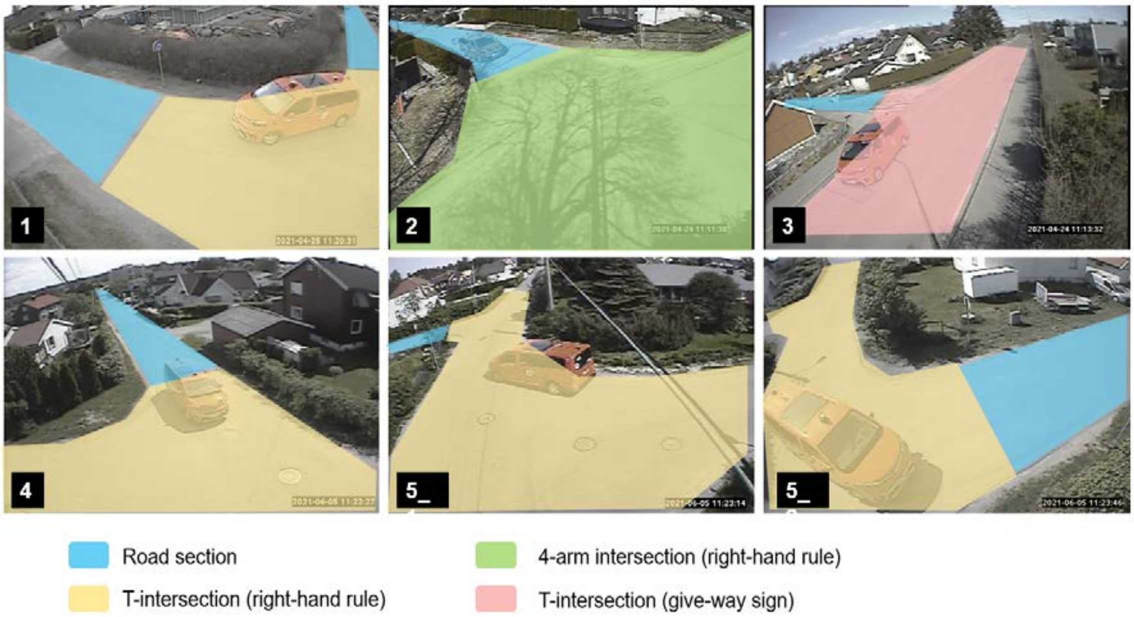


Figure 3.1: Decomposition of the observed locations into single layout categories.

Table 3.1: Overview of infrastructure layout categories on every location.

Infrastructure layout category	location					
	#1	#2	#3	#4	#5_1	#5_2
Road section	x	x	x	x	x	x
T-intersection with right-hand priority rule	x			x	x	x
4-arm intersection with right-hand priority rule		x				
T-intersection with give-way sign priority			x			

3.2 Shuttle volumes and number of interactions

We collected 328 hours of video (168 in April and 160 in June) and detected 956 shuttle passages. The detection rate was 100 %. Table 3.2 shows the daily numbers of detected passages on every location.

Table 3.2: The daily numbers of detected shuttle passages.

	Sat. 24.4.	Sun. 25.4.	Mo. 26.4.	Tu. 27.4.	Wed. 28.4.	Th. 29.4.	Fr. 30.4.
Location #1	39	35	36	34	25	16	19
Location #2	39	35	36	34	25	16	19
Location #3	39	36	36	34	26	18	19
	5.6.	**6.6.**	**7.6.**	**8.6.**	**9.6.**	**10.6.**	**11.6.**
Location #4	15	19	14	19	20	19	12
Location #5_1	15	19	14	19	20	19	n.a.
Location #5_2	15	19	14	19	20	19	10

The low numbers of detected passages in some of the days (28-30/4; 5-11/6) indicate that only one vehicle was in operation. In addition to that, in four days (25/4; 28/4; 29/4; 11/6), shuttle deviated from its route, and therefore was not captured by the camera on some locations. Furthermore, camera #5_1 ran out of the battery on 11/6, therefore there are no recordings from this day. However, it was possible to supplement the missing data with camera #5_2.

The analyses of video clips revealed 193 situations, in which the shuttle had an interaction with another road user or performed oddly without any obvious traffic related stimuli. Table 3.3 summarizes the numbers of interactions for each road user type and infrastructure category.

Table 3.3: Numbers of interactions for each infrastructure category.

Infrastructure layout	Interaction with				
	Vehicle	Pedestrian	Bike	Other	Total
Road section	21	37	5	4	67
T-intersection (right-hand rule)	29	14	4	7	54
4-arm intersection (right-hand rule)	17	4	3	1	25
T-intersection (give-way sign	42	3	2	0	47
Total	109	58	14	12	193

Most (35 %) situations were observed along the road sections, where interactions with pedestrians were the most frequent. As for the type of involved road users, the interactions with motorised vehicles (almost exclusively with passenger cars) made up more than half of all the interactions. These were most frequent on T-intersection with give-way sign, where the shuttle was entering the main road with higher car volumes.

The interactions categorised as “other” were mostly situations in which the shuttle stopped without any visible reason.

3.3 Road sections

There were 67 situations observed along six road sections. Table 3.4 shows the variety of situations that the shuttle was encountering (sorted by road user type and the moving patterns).

Table 3.4: The situations sorted by each road user type and the moving patterns.

Road user	Moving pattern	No. of situations
Pedestrians (n=37)	walking/standing on the road - right	24
	walking/standing on the road - left	8
	walking/standing on both sides parallel	3
	walking/standing on the road - middle	1
	entering the road from side	1
Vehicles (n=21)	passing in opposite direction	12
	parked along the road	7
	entering the road from side	2
Bikes (n=5)	riding on the road - left	4
	riding on the road - right	1
Other (n=4)	not relevant	4

Most of the interactions involved a pedestrian, walking or standing on the right side of the road (at the same side as the shuttle was driving). In those situations the shuttle was in manual mode, because the shuttle drivers were instructed to proactively take over the driving in those situations (in order to avoid unnecessary stops). The shuttle drivers typically slowed down and drove around the pedestrian, keeping a significant lateral passing distance (Figure 3.2). When a pedestrian was on the left side of the road, the shuttle stayed in automated mode and continued to drive without slowing.

Figure 3.2: Examples of two situations at location #4 in which the shuttle (in manual mode) drives around a pedestrian (left – clip #1, right – clip #2).

Regarding pedestrians, there was one situation that is worth highlighting, as it demonstrates the variability of scenarios that the shuttle might encounter in residential areas (Figure 3.3). In this situation on location #1, a kids' bike was lying in the middle of the road. When the shuttle was exiting the intersection, a man entered the road from the left, behind a parked car, to pick up the bike. A child entered the road as well. In this situation, the shuttle was probably in automated mode. It reacted well and stopped (hard).

*Figure 3.3: Positions of pedestrians and the shuttle in the moment of the hard stop (**clip #3**).*

Regarding the situations involving vehicles (n=21), most of them were situations in which a vehicle was driving/was parked in the opposite direction. In those situations the shuttle did not react in any, except one, situation, in which it stopped because of a moped (location #5, Figure 3.4). In the situations involving a car parked on the right side of the road, the shuttle drove slowly around, probably in manual mode.

*Figure 3.4: The shuttle (in automated mode) stops because of a moped riding in the opposite direction (**clip #4**).*

3.3.1 Inadequate reactions of the shuttle

There were seven inadequate reactions identified along the road sections. In four situations the shuttle stopped without a visible reason (3 x on location #1, once on location #3). In three other situations the shuttle (i) stopped after overtaking a parked car (location #1), (ii) the shuttle followed a pedestrian for a while (location #1) and (iii) the shuttle stopped because of a moped in the opposite direction (Figure 3.4).

3.4 T-intersections (right-hand priority rule)

There were 54 situations observed at four T-intersections. Table 3.5 shows the variety of situations that the shuttle was encountering (sorted by each road user type and the moving patterns). We assume, that the shuttle was in automated mode in most of these situations.

The most frequent types of situations were (i) a motorised vehicle (almost exclusively passenger cars) approaching from left or right and driving straight through the intersection; (ii) a pedestrian walking on the right sight of the road inside the intersection; and (iii) situations categorised as “other”. In most of the situations (67 %) the shuttle stopped, and 21 stops (58 %) were estimated as not smooth (Table 3.6).

Table 3.5: The situations sorted by the road user type and moving pattern.

Road user	Moving pattern	No. of situations
Vehicles (n=29)	driving from left - straight	11
	driving from right - straight	7
	driving from right - turning left	5
	driving from left – turning right	5
	standing in the middle of the road	1
Pedestrians (n=14)	walking along right side	6
	walking along left side	3
	crossing from right	2
	walking in middle of the road	2
	standing on right side	1
Bikes (n=4)	riding on the left	2
	riding on the left - turning right	2
Other (n=7)	not relevant	7
Total		54

Table 3.6: Types of shuttle’s reactions.

Reaction	Intensity	No. of reactions	% of all
Stop	hard	11	20 %
	less hard	10	19 %
	smooth	13	24 %
	almost	2	4 %
Slowing down		8	15 %
Driving around		2	4 %
None		8	15 %
Total		54	100 %

3.4.1 Inadequate reactions of the shuttle

Sixteen reactions of the shuttle were evaluated as inadequate. Six of them were the stops without a visible reason; in one situation the shuttle reacted to a bird that crossed the shuttle’s trajectory (Figure 3.5).

*Figure 3.5: The moment when the magpie crossed the shuttle trajectory (**clip #5**).*

Three situations included a pedestrian. In one situation, the shuttle stopped when the pedestrian was walking along the left side of the road (location #1, Figure 3.6 - left). The other situation involved a child and a man who were walking close to the middle of the road. There was a parked car on the left side of the road as well (location #1, Figure 3.6 - right). The shuttle detected them and stopped hard. This reaction was on the border between adequate and inadequate, as it provided a comfortable/safe space for pedestrians, but the braking was very hard and thus uncomfortable to any passengers inside the shuttle.

Figure 3.6: *Positions of pedestrians and the shuttle in the moment of the hard stop (left: **clip #6**; right: **clip #7**).*

In the third situation, the shuttle stopped too early to give way to the pedestrian from the right (location #4, Figure 3.7). It seemed that the shuttle driver took over the driving to solve the situation.

Figure 3.7: In this moment the shuttle has been already stopped for five seconds and the driver took over driving (clip #8).

Six inadequate reactions involved a motorised vehicle. All were observed on location #5. In three situations the vehicle was approaching from left and the shuttle was turning right. In two of those, a motorcycle and a passenger car had already driven through the intersection, but the shuttle stopped anyway (ca. five seconds after the vehicle drove away). These reactions were classified as unnecessary, delayed stops (Figure 3.8). In the third situation, the car from the left did not give way to the shuttle, the shuttle stopped and stayed stopped for ca 20 seconds (too long stop).

Figure 3.8: The positions of the shuttle and motorised vehicles in the moment of the shuttle's reaction (left: clip #9; right: clip #10).

In three situations, a vehicle was approaching from the right. These were not "give way" situations, as the shuttle was turning right. However, the relatively narrow road required careful maneuvering (Figure 3.9). In two of these situations the shuttle stopped on the approach (Figure 3.10). This was a correct reaction, however the stops were hard and therefore classified as inadequate.

Figure 3.9: Scheme of the situation.

*Figure 3.10: The positions of the shuttle and cars in the moment of the shuttle's reaction (left: **clip #11**; right: **clip #12**).*

In the third situation, the shuttle entered the intersection despite a car approaching from the right. After detecting the car, the shuttle stopped inside the intersection (and stayed stopped for 12 seconds) and the car made a slight avoidance maneuver. This situation was classified as a conflict (Figure 3.11).

*Figure 3.11: Positions of the car and the shuttle, when the shuttle stopped (**clip #13**).*

3.4.2 Give-way situations with cars from left (the shuttle has a priority)

From 11 give-way situations with a car driving from the left and continuing straight, we observed eight situations in which the car drivers were not giving way to the shuttle. Three such situations were observed on location #1 (Figure 3.12) and five on location #5. In all these situations, the cars should have yielded to the shuttle according to the right-hand yielding rule. In all situations, the shuttle stopped hard. In two situations the cars were clearly accelerating to avoid giving way. In several situations, the cars have already been exiting the intersection at the moment the shuttle stops. We did not consider such stops as inadequate, because they were triggered by illegal behaviour of the car drivers.

Figure 3.12: Positions of cars and the shuttle in the moment of the hard stop of the shuttle (from left: clips #14; #15 and #16).

One of situations on location #5 was considered as a conflict, as the shuttle had to stop hard to avoid crashing with the car. The car also made an evasive maneuver (Figure 3.13).

Figure 3.13: Positions of the car and the shuttle, when the shuttle stopped (clip #17).

3.4.3 Give-way situations with cars from the right (the shuttle does not have a priority)

When the shuttle was supposed to give way, the shuttle did so. In one situation, on location #4, both the shuttle and the car stopped and the car drove first after a while. This was classified as "stale-mate" situation (Figure 3.14).

Figure 3.14: "Stalemate" situation – both vehicles have stopped (clip #18).

3.5 Four-arm intersection (right-hand priority rule)

There were 25 situations observed on one 4-arm intersection (location #2). Table 3.7 shows the variety of situations that the shuttle was encountering (sorted by road user type and the moving patterns). We assume, that the shuttle was in automated mode in most of these situations.

The most frequent types of situation involved a motorised vehicle (almost exclusively passenger cars) approaching from left or right and driving straight through the intersection.

Table 3.7: Situations sorted by road user type and the moving pattern.

Road user	Moving pattern	No. of situations
Vehicles (n=17)	driving from left - straight	6
	driving from right - straight	4
	driving from right - turning left	1
	driving from right - turning right	2
	driving from opposite - turning left	1
	driving from opposite - passing	3
Pedestrians (n=4)	walking from left - straight	3
	walking from right - straight	1
Bikes (n=3)	riding from left - straight	1
	riding from right - straight	1
	riding in opposite - passing	1
Other (n=7)	not relevant	1
Total		25

Table 3.8 shows the types of reactions by the shuttle. In most of the situations (80 %) the shuttle stopped, most often smoothly.

Table 3.8: Types of reactions by the shuttle.

Reaction	Intensity	No. of reactions	% of all
Stop	hard	1	4 %
	less hard	4	16 %
	smooth	13	52 %
	double	1	4 %
	almost	1	4 %
Slowing down		3	12 %
None		2	8 %
Total		25	100 %

3.5.1 Inadequate reactions by the shuttle

Nine reactions by the shuttle were evaluated as inadequate. Seven involved a motorised vehicle, one involved a pedestrian and one situation involved only the shuttle. In situations involving motorised vehicles, four reactions were delayed stops (by ca. 4-5 seconds) as a late reaction to a vehicle from the left that had already exited the intersection (such as the one on Figure 3.15).

Figure 3.15: Positions of a car and the shuttle 4 seconds before the shuttle stops (clip #19).

In two situations, the shuttle stopped during a passing interaction with vehicles in the opposite direction. The vehicles were probably inside the shuttle's safety zone, however there was still enough space to drive. One stop occurred in the middle of the intersection, another on the approach (Figure 3.16).

Figure 3.16: Moments of stops in passing situations (left: clip #20; right: clip #21).

In the last situation with a motor vehicle, the shuttle stopped too hard when there was a mini post-van approaching from the right.

In the remaining two situations, the shuttle (i) stopped on the approach without any visible reason and (ii) the shuttle stopped probably as a reaction to the pedestrians who were however far away from the shuttle.

3.5.2 Give-way situations with road users from the left (shuttle has a priority)

There were four situations (one with a car, one with a child on a bike and two with pedestrians) in which the shuttle had the right of way but had to stop, because the other road user did not give way to the shuttle (Figure 3.17). The situation with the child on the bike (clip #23) might be considered as “stale-mate “ situation, as both the shuttle and the child slowed down and the child decided to continue once the shuttle stopped.

Figure 3.17: Positions of the shuttle and the other road users in the moment when the shuttle stopped (left: clip #22; right: clip #23).

3.5.3 Give-way situations with cars from the right (shuttle does not have a priority)

In seven situations, in which a car was approaching from the right, the shuttle gave way as it should. In several of these situations, the shuttle behaved perhaps too defensively (stopping too early), but these stops were not evaluated as an inadequate reaction.

3.6 T-intersection (give-way sign priority)

There were in total 47 situations observed at one T-intersection with give-way sign (location #3). We assumed that the shuttle was in automated mode in most of the situations. Table 3.9 shows the variety of situations that the shuttle was encountering there (sorted by the moving pattern for each road user type). The most frequent types of situation involved a shuttle approaching along the minor road and a motorised vehicle (almost exclusively passenger cars) approaching from the left along the main road and driving straight through the intersection.

Table 3.9: Situations sorted by road user type and the moving pattern.

Road user	Moving pattern	No. of situations
Vehicles (n=42)	driving from left - straight	34
	driving from left - turning right	3
	driving from right - turning left	5
Pedestrians (n=3)	walking from left	3
Bikes (n=2)	riding from left - straight	2
Total		47

Table 3.10 shows the types of shuttle’s reactions. In most of the situations (80 %) the shuttle stopped, mostly smoothly.

Table 3.10: Types of shuttle’s reactions.

Reaction	Intensity	No. of reactions	% of all
Stop	hard	9	19 %
	less hard	5	11 %
	smooth	23	49 %
	double	1	2 %
	almost	1	2 %
Slowing down		6	13 %
None		2	4 %
Total		47	100 %

The shuttle detected all road users and all situations were solved according the traffic rules.

3.6.1 Inadequate reactions of the shuttle

Eight reactions of the shuttle were evaluated as inadequate (six with a passenger car, one with a bike and one with a pedestrian). In situations involving passenger cars (all driving from the left) the shuttle stopped very hard in five situations and in one situation the shuttle stopped too early (Figure 3.18).

*Figure 3.18: The shuttle stops too early/unnecessary when giving way to passing car. Position of shuttle and car when the shuttle stops (**clip #24**).*

The shuttle stopped too hard in one situation that involved a cyclist approaching from the left. In the situation that involved a pedestrian, two pedestrians were crossing the zebra crossing from the left and the shuttle stopped intermittently (i.e. a multiple stop).

4 Conclusion and Discussion

4.1 Conclusion

During two observational periods in residential area Hebekk, we recorded 328 hours of video on five locations. From these, we detected 956 shuttle passages. We recognised and analysed 193 situations, in which the shuttle interacted with another road user, or performed oddly without anybody/anything in its proximity. Most situations involved a passenger car (n = 109) or a pedestrian (n = 58). We did not observe any accident. We identified two conflicts, the first caused by a car driver, the second by the shuttle in automated mode.

In situations involving pedestrians walking along the right side of the road sections, the shuttle was driven in manual mode (the drivers were instructed to proactively take control as the shuttle was not able to adequately react to pedestrians walking within the shuttle's safety zone).

In situations at intersections, the shuttle was supposed to be in automated mode.[6] The shuttle in automated mode detected all the relevant road users and reacted to them. Some of the reactions were inadequate (such as hard or too long stops), mostly at right-hand priority intersections. If another road user behaved in conflict with the traffic rules, the shuttle recognised that and reacted. In some situations, the shuttle stopped without an obvious reason. From a safety perspective, the most disturbing finding regards the car drivers not giving way to the shuttle at the intersections with right-hand yielding rule.

These findings are in accordance with previous studies on performance of automated shuttles in the Oslo region that TØI has recently conducted (De Ceunynck et al., 2022; Pokorny et al., 2021a; Pokorny et al., 2021b).

4.2 Discussion

4.2.1 Inadequate reactions of the shuttle

Of 193 situations, the shuttle reacted inadequately (given the context of the situation) in 40 situations. Most of these reactions were different types of stops that were inadequate because of their intensity, timing, purpose or duration (such as too hard, too early, unnecessary or delayed stop). Overall, these reactions can be attributed to the "defensive" style of the shuttle's decision making and the strict reactions when an object is detected inside the shuttle's safety zone/priority area.

Table 4.1 and Table 4.2 summarize the shares of inadequate reactions for each infrastructure layout and road user category. The share of inadequate reactions was highest at intersections with right-hand yielding rule. This is not surprising, as these locations are more demanding both with regards to the interaction itself as well as how to interpret traffic

[6] *We made the effort to link the time of the situations with the data about the shuttle mode status at the same time, however sometimes the mode remained unclear.*

situations correctly than road sections or intersections with a give way sign. Regarding other road users, the highest share of inadequate reactions was found in situations with passenger cars. The low share of inadequate reactions in situations with pedestrians can be explained by the fact that the shuttle was driven manually in most interactions involving pedestrians. The 100% share of inadequate reactions in situations categorised as “other” is based on the very definition of these situations (i.e. situations when the shuttle reacted strangely without any visible reason).

Table 4.1: Share of inadequate reactions from all situations for particular infrastructure layout.

Infrastructure layout	No. of situations	No. of inadequate situations	% of inadequate situations
Road section	67	7	10 %
T-intersection (right-hand rule)	54	16	30 %
4-arm intersection (right-hand rule)	25	9	36 %
T-intersection (give-way sign)	47	8	17 %

Table 4.2: Share of inadequate reactions from all situations for particular road user type.

Road user	No. of situations	No. of inadequate reactions	% of inadequate reactions
Motorised vehicle	109	21	19 %
Pedestrian	58	6	10 %
Bicycle	14	1	7 %
Other	12	12	100 %

From the 40 inadequate reactions, one was categorised as a conflict caused by the shuttle (Figure 3.11).

In general, the inadequate reactions, especially hard and unexpected stops, might by risky for other road users. The intensity and suddenness of these stops can increase the risk of rear-end accidents. However, such rear-end situations were not observed. Furthermore, hard and unexpected stops might be uncomfortable for the passengers inside the shuttle.

4.2.2 Other safety concerns

From a safety perspective, the most disturbing finding refers to the fact that we observed several car drivers not giving way to the shuttle at the intersections with right-hand yielding rule. In 17 give-way interactions between the shuttle and a car, we observed 9 situations (53 %) in which drivers did not give way to the shuttle. One of these situations was considered as a conflict, as the shuttle had to stop hard to avoid crashing into the car. The car also made an evasive maneuver (Figure 3.13).

We observed such behaviour also in ordinary car-car interactions, however not so frequently - from 19 give-way interactions, in 6 cases (32 %) drivers did not yield to an ordinary car from the right.

The “not giving-way” behaviour of car drivers in interactions with automated shuttle could have been caused by the slow speed and strict and defensive driving style of the shuttle, which could encourage some drivers to misuse/take advantage of such style. This would be in line with theoretically expected responses to automated shuttles(Bjørnskau, 2017; Michieli & Badia, 2018; Millard-Ball, 2018).

A high number of children in the roads in Hebekk presents another important safety concern. Children are more difficult to detect and more unpredictable than other road user. However, we did not observe any unsafe situations in interactions with children.

Another potentially problematic issue concerns the inconsistency of the shuttle's mode. The shuttle switched often between manual and automated modes. Despite these two modes often being visually distinguishable, some road users can misjudge the shuttle's mode and her/his expectancies regarding the shuttle performance might not be matched with the reality. This may in particular be a problem to those who encounter the shuttle frequently and who have developed certain expectations towards the shuttles' behaviour.

Finally, it is obvious that the interactions with pedestrians are frequent in Hebekk. To ensure a smooth and automated operation of the shuttle in Hebekk, the shuttle must be able to solve these situations in automated mode, safely and without stopping.

4.3 Limitations

Within the analyses, we evaluated safety of the interactions from the perspective of an external observer. We did not evaluate the correctness of the shuttle's performance according to how it was programmed.

The method of external observation has its limitations linked with the observer's potential misperception and subjective judgment of the traffic situations. For example, we can only estimate the reasons for the observed behaviour, as we have no detailed knowledge about the involved road users, their intentions and why they behave in the observed way. When we observed that car drivers do not give way to the shuttle, it might be that some of them were not aware of the priority rule, rather than trying to take advantage of the defensive driving style of the shuttle. In addition to that, the observer has a limited view of the evaluated situations, restricted by the camera angle view.

Furthermore, there were a few situations when it was unclear whether the shuttle was in automated mode or driven by the driver.

Transferability of results into other contexts and countries is limited because of different driving cultures and infrastructure specifics. Furthermore, the rapid pace of technological development limits the validity of the results for the future versions of the shuttles. Therefore, the continuous research effort is needed to capture the newest versions of the shuttles.

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