Image-based assessment of road network readiness for automated driving

A judgement game

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Spatial and Transport Impacts of Automated Driving

Image-based assessment of road network readiness for automated driving:

A JUDGEMENT GAME

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1. INTRODUCTION

Automated Driving (AD) is expected to deliver various benefits beyond those possible with manual driving for transport systems and the environment, yet there are many uncertainties with respect to the development path of AD to full automation. (SAE International, 2016) defines five levels of vehicle automation summarized in Figure 1. Automated driving system (ADS) can take over more driving tasks at higher automation levels until finally at level 5, ADS can handle the full range of driving complexity and it is feasible in all driving modes. However, the transition period to full automation might be long and full of uncertainties.

Two incremental paths toward full automation have been observed so far. (CPBR, 2015) describes them as “something everywhere” and “everything somewhere”. Most traditional car manufacturers are embracing “something everywhere” path, i.e., gradually improving ADS in existing vehicles and shifting more driving tasks from the driver to ADS over time. Then the user is responsible for using the ADS wisely. This is also consistent with SAE automation levels. The other alternative, which was recently adapted by Google, involves aiming at full automation within a limited domain (e.g., only certain road types) and expanding this domain to more road types and more complex driving situations. This means the absolute ADS autonomy can only be realized in specific conditions. Then the challenge is to define those conditions specifically.

For both paths, infrastructure is a defining factor. It can either facilitate or prevent higher automation capabilities. During the transition period to full automation, safe operation of levels 3-4 at their full automation capacity will highly depend on the type of infrastructure they encounter. For road authorities it is important to know how ready the road infrastructure is for safe automated driving. However, the academic literature and the field reports do not offer sufficient information to answer this question. (Farah et al., 2018) point out numerous knowledge gaps regarding infrastructure for AD. Therefore, we embarked on providing some insight into the matter via an expert workshop.

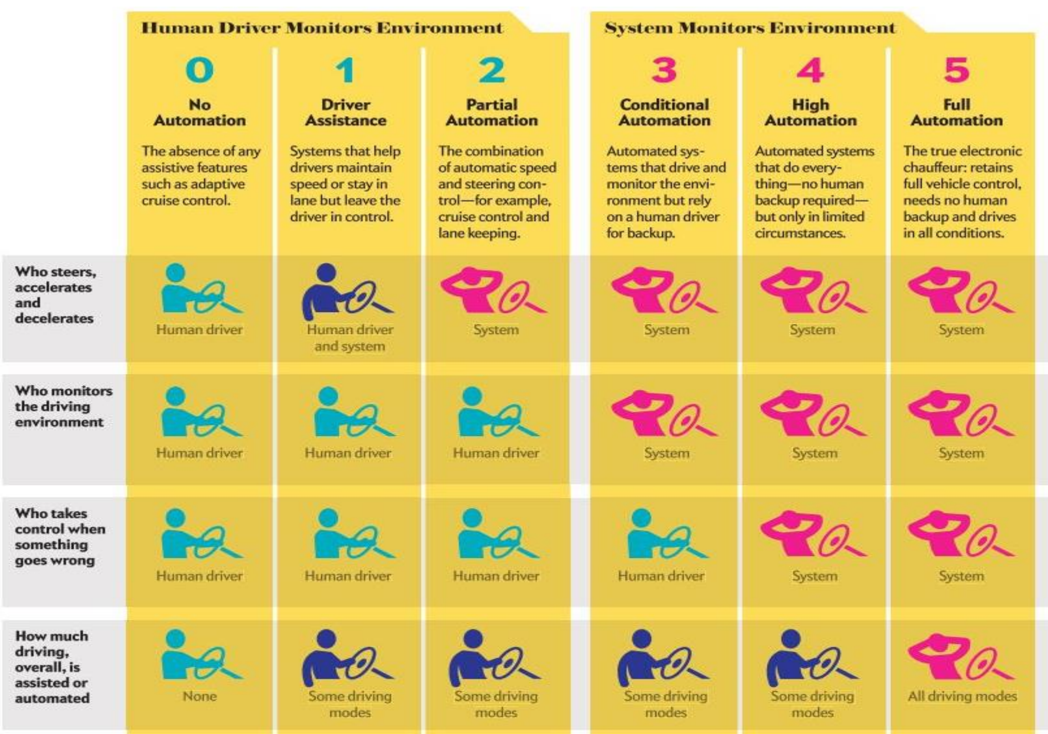

Figure 1: Levels of automation (Shladover, 2016)

1.1. Research questions

The following research questions were formulated to be investigated during the workshop:

- On which road types it is safe to facilitate AD?
- On which intersection types it is safe to facilitate AD?
- Can we derive specific rules and physical requirements for road and intersection types that can safely accommodate AD?

1.2. Scope

The following scoping choices were made for the workshop in order to guarantee a meaningful and efficient discussion; we focus on the transition period to full automation with a mix of different levels of automation (i.e., levels 0-4 mixed) in urban regions. We do not consider extreme weather conditions, emergency situations and road works.

2. WORKSHOP AND RESULTS

Since infrastructure requirements can be case-dependent, we attempted to have a systematic approach for investigating various types of infrastructure segments. In order to have clear and tangible situations in mind, we decided to prepare images of specific places and ask experts direct questions about each situation. Several attributes were associated with each picture and we tried to prepare a selection of images that covers a wide range of potential issues. The following section describes the workshop in details and summarizes the results.

Figure 2 Example image of a road segment presented in the workshop

2.1. Workshop: The Judgement Game

The workshop included two rounds of judging images of specific infrastructure segments by experts followed by a group discussion after each round and a summary at the end. In the first round, the experts were presented with 20 pictures of road segments (Appendix C) and were asked the following:

- Please answer with yes or no; is it safe to allow AD in the place represented by the picture?
- When your answer is no, please specify potential issues or risks related to the situation in short keywords and (if possible) suggest solutions to remedy the situation.

An example image from the workshop is presented in Figure 2 and the entire collection of images used in the workshop can be found in Appendices C & D. A discussion was held at the end of this round to consider some controversial situations in detail, to identify potentially problematic situations in general, and to determine considerations for decision making. In the second round, the same procedure was repeated with 20 pictures of intersections (Appendix D) and the workshop ended with a summary session.

2.2. Results

Five attributes were identified for each road image (Table 1) to classify it based on road type, road function, speed, capacity and road users. Responses of experts, identified issues and suggested solutions are presented in Table 2. For intersections, six attributes with binary (yes or no) values were used to distinguish the type of intersection and its users (Appendix A: Table 6). Table 7 (in Appendix A) summarizes the responses, identified issues and suggested solutions for intersections.

Table 1: Road attributes (C: car, T: truck, Pt: public transport, Am: active modes)

Road Number	Road Type	Road Function	Speed	Capacity	Users
1	A-road	Flow	High	High	CT
2	A-road	Flow	High	High	CT
3	A-road	Flow	High	High	CT
4	N-road	Flow	High	High	CT
5	N-road	Flow	High	High	CT
6	N-road	Flow	High	High	CT
7	S-road	Distributor	Medium	Medium	CT
8	S-road	Distributor	Medium	Low	CTPtAm
9	S-road	Distributor	Medium	Medium	CT
10	S-road	Distributor	Medium	Medium	CT
11	S-road	Flow	Medium	Medium	CT
12	S-road	Flow	Medium	Medium	CT
13	S-road	Flow	Medium	Medium	CT
14	S-road	Flow	Medium	Medium	CT
15	Local-road	Distributor	Medium	Low	CT
16	Local-road	Distributor	Medium	Low	CTPtAm
17	Woonerf	Access	Low	Low	CTAm
18	Woonerf	Access	Low	Low	CTAm
19	Woonerf	Access	Low	Low	CTAm
20	Fietsstraat	Access	Low	Low	CTAm

Table 2: Responses for roads (VRU: vulnerable road user)

Road Number	Response		Key words (issues)	Solution
	YES	NO		
1	6	2	lane number, direction signs	-
2	5	2	lines	-
3	3	4	lane markings, information (2)	-
4	7	1	-	-
5	7	0	-	-
6	7	0	-	-
7	6	1	lane markings	-
8	3	6	bike lane (2), tram line, road users	low speed
9	6	1	parked cars (3)	-
10	9	0	-	-
11	6	2	unpredictable conflict	-
12	8	0	-	-
13	6	1	road sign	-
14	2	5	VRU (3)	low speed & digital map
15	6	3	VRU (2)	digital map & no parked car
16	1	8	road users (2), complexity (2)	-
17	4	5	VRU, parked cars	low speed
18	2	6	VRU, complexity, overview	low speed
19	3	5	VRU	low speed
20	3	5	lane markings (2), VRU	low speed

Results reveal that many similar issues were identified for different instances of both roads and intersections. Overall, 17 issues (Table 8) and 5 solutions (Table 9) were suggested for 40 images. Most of these issues can potentially cause problems for experienced human drivers as well (e.g., double right of the way signs or unclear road signs) yet these situations exist in almost any city and human drivers find a way to cope with them. ADS on the other hand, can face serious challenges for decision making when confronted with such situations. These issues can be used as a checklist of “no goes” for road authorities and road designers to consider when allowing AD in urban regions or when designing new roads to accommodate AD.

Regarding road and intersection attributes and responses, clear correlations were rare; nonetheless, some patterns were discernible with respect to road function and road users. As it can be seen in Figure 3, with a change in road function from access to distribution and from distribution to flow, the acceptance rate increases. That is, roads with flow function tend to be the safest ones for AD and roads with distribution function are more likely to be safe for AD compared to roads with access function. A rather similar pattern is observable in Figure 6 regarding road users; roads on which only cars and trucks are allowed tend to be the safest and with the addition of active modes (pedestrians and cyclists) and public transport (i.e., buses and trams) acceptance rate gradually decreases. This suggests that a general safety hierarchy can be hypothesized for roads based on road function and road users.

In order to test this hypothesis (the existence of this correlation), a two way ANOVA test for response (percentage “yes” from experts) using a 4-factor complete model with road attributes (namely, function, users, type and speed) as factors was performed and the results confirm that road function and road users are significant factors in predicting responses (Table 3). The same test was performed for intersection attributes, however no significant factor was found in this case (Table 11). Figures 5-15 demonstrate the relation between responses and attributes for both roads and intersections.

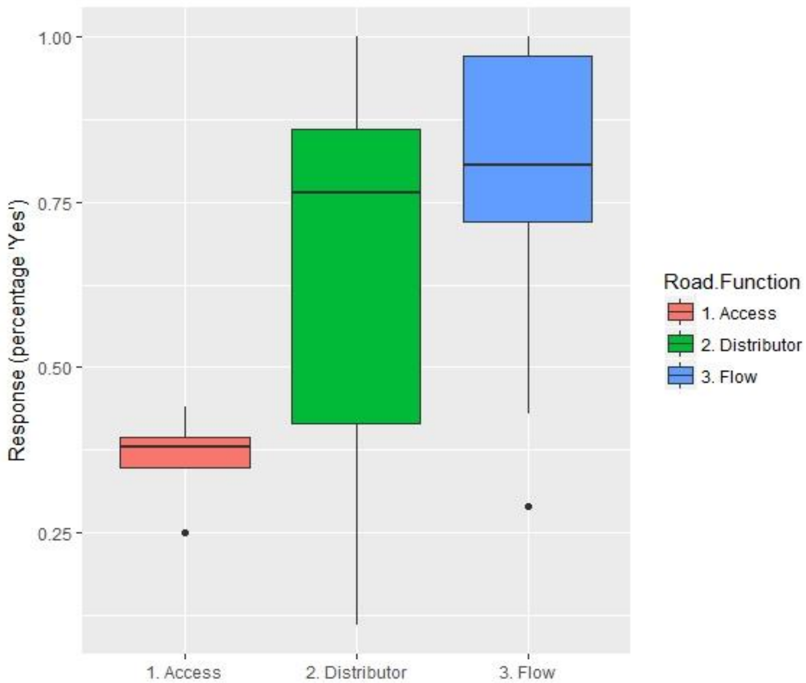

Figure 3 Response for road function categories

Table 3: Two Way Analysis of Variance for road responses based on road attributes (stars indicate significant factors)

Response: y (yes%) 4-factor complete model

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Function	2	0.46821	0.23410	6.6708	0.012669 *
Speed	1	0.01176	0.01176	0.3351	0.574333
Users	1	0.52501	0.52501	14.9601	0.002618 **
Type	3	0.22988	0.07663	2.1835	0.147562
Users: Type	1	0.00008	0.00008	0.0024	0.962008
Residuals	11	0.38603	0.03509		

2.3. Summary of discussions

There were two rounds of discussions one after the judgement round for roads and one after the intersection round. Here we provide two separate summaries of discussions.

2.3.1. Discussion on roads

For the discussion on roads, first some generally problematic situations were debated. They include unpredictable active mode crossings, parked cars on the side of the roads, and rather high speed roads with bicycles. The main trigger for this discussion was road image R16 (Appendix C); yet there was a consensus among experts that these are recurring issues and they can be even more problematic for automated vehicles. These relate to two main principles of Sustainable Safety (Wegman et al., 2008), namely, clear expectations from the road and mono-functionality of the road. Although in theory, roads in the Netherlands are expected to comply with these principles, in practice, this is not always the case.

The next topic in the discussion of roads was general guidelines for design and concepts to consider while decision making. The first item in this topic was a reflection on the combination of safety requirements and speed requirements based on road image R3 (Appendix C). Since lower speed was the solution suggested by some experts for different issues, even in some cases where higher speeds were required from the road, some others pointed out that the trade-offs between safety and speed requirements should be taken into account and lower speed cannot be the solution for every conflict. All experts agreed that despite the speed, user expectations from the road should be clear though. Another subject for debate was segregation of traffic and limiting access to roads in some places to improve safety. This led to the next controversy in the discussion; one argument was that infrastructure adjustments for AD must comply with other ideas of a liveable city. The counterargument was that it is more sensible to stick to the Sustainable Safety principles that have already been in place in the Netherlands for a long time and are currently the main reference for road design.

2.3.2. Discussion on intersections

The discussion on intersections basically boiled down to the following list of requirements for intersections to accommodate AD:

- Conflicts with active modes on intersections should be restricted to low speeds.
- When there are too many directions, traffic lights are a must.
- Complex intersections are only possible with lane markings and digital maps.
- Some problems that are less important with regular drivers become more important with AVs (e.g., double right of the way signs); most of these problems are easily fixable but they should be dealt with before having AVs on the roads.
- Sun and shadow can lead to lack of contrast around traffic lights; AV traffic light detection technology must be robust.
- Roundabouts can be problematic in congested situations; eye contact is required.
- Digital maps can help with bicycle crossings from unexpected places.

3. CONCLUSIONS

Based on the results of this workshop, we can predict some potentially problematic road and intersection situations for AD and the relevant factors involved. Obviously, more comprehensive situation types judged by more experts, and real world tests are required to verify these findings. Nonetheless, we believe this is an appropriate starting point for a systematic approach to determine infrastructure requirements for AD.

Moreover, a general hierarchy for safety of road types based on road function and road users was suggested in the results section that can be used to define priority for choosing roads to allow for AD, and to be aware of road types that potentially require more attention when facilitating AD. As for the intersections, a list of requirements for intersections to safely accommodate AD was suggested in the discussion section.

Finally, it should be noted that with proper adjustments, any road segment or intersection can become safe for AD. However, these adjustments can be costly; the key challenge is considering the trade-offs between the adjustment costs and the benefits offered by these adjustments.

4. REFERENCES

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APPENDIX A: TABLES

Table 4: Road attributes (copy of Table 1)

Road Number	Road Type	Road Function	Speed	Capacity	Users
1	A-road	Flow	High	High	CT
2	A-road	Flow	High	High	CT
3	A-road	Flow	High	High	CT
4	N-road	Flow	High	High	CT
5	N-road	Flow	High	High	CT
6	N-road	Flow	High	High	CT
7	S-road	Distributor	Medium	Medium	CT
8	S-road	Distributor	Medium	Low	CTPtAm
9	S-road	Distributor	Medium	Medium	CT
10	S-road	Distributor	Medium	Medium	CT
11	S-road	Flow	Medium	Medium	CT
12	S-road	Flow	Medium	Medium	CT
13	S-road	Flow	Medium	Medium	CT
14	S-road	Flow	Medium	Medium	CT
15	Local-road	Distributor	Medium	Low	CT
16	Local-road	Distributor	Medium	Low	CTPtAm
17	Woonerf	Access	Low	Low	CTAm
18	Woonerf	Access	Low	Low	CTAm
19	Woonerf	Access	Low	Low	CTAm
20	Fietsstraat	Access	Low	Low	CTAm

Table 5: Responses for roads (copy of Table 2)

Road Number	Response		Key words (issues)	Solution
	YES	NO		
1	6	2	lane number, direction signs	-
2	5	2	lines	-
3	3	4	lane markings, information (2)	-
4	7	1	-	-
5	7	0	-	-
6	7	0	-	-
7	6	1	lane markings	-
8	3	6	bike lane (2), tram line, road users	low speed
9	6	1	parked cars (3)	-
10	9	0	-	-
11	6	2	unpredictable conflict	-
12	8	0	-	-
13	6	1	road sign	-
14	2	5	VRU (3)	low speed & digital map
15	6	3	VRU (2)	digital map & no parked car
16	1	8	road users (2), complexity (2)	-
17	4	5	VRU, parked cars	low speed
18	2	6	VRU, complexity, overview	low speed
19	3	5	VRU	low speed
20	3	5	lane markings (2), VRU	low speed

Table 6: Intersection attributes (Y: yes, N: no, S: single, M: multiple)

Intersection Number	Signal	Active modes	PT	Roundabout	Lanes	Priority
1	N	Y	N	Y	S	Y
2	N	Y	Y	Y	S	Y
3	N	N	N	Y	S	Y
4	N	Y	Y	Y	S	Y
5	Y	Y	Y	N	M	Y
6	Y	Y	N	N	S	Y
7	N	Y	Y	N	M	Y
8	Y	Y	Y	N	M	Y
9	N	Y	N	N	M	Y
10	Y	Y	Y	N	M	Y
11	Y	Y	N	N	M	Y
12	Y	Y	Y	N	M	Y
13	Y	Y	Y	N	M	Y
14	Y	Y	N	N	M	Y
15	N	Y	N	N	S	N
16	N	Y	Y	N	S	Y
17	N	Y	Y	N	M	Y
18	N	Y	Y	N	M	Y
19	Y	Y	N	N	M	Y
20	N	Y	N	N	S	Y

Table 7: Responses for intersections (VRU: vulnerable road user)

Intersection Number	Response		Key Words (issues)	solutions
	YES	NO		
1	2	6	lane marking (4), road users (2)	-
2	5	5	road users (3), eye contact	-
3	8	1	eye contact	-
4	5	3	priority signs, bike lane, conflicts	-
5	4	5	directions (5)	-
6	8	0	-	-
7	6	2	directions, road users, VRU	low speed (2)
8	6	1	lane marking	digital map (2)
9	4	5	VRU (4)	
10	5	2	tram lines (2)	traffic lights (2)
11	7	0	-	-
12	7	2	lane marking, complexity	-
13	3	5	VRU (2), conflicts, complexity	digital maps, traffic lights
14	7	1	bike lane	-
15	7	1	eye contact	low speed (3)
16	4	3	tram line, road users	traffic lights & rearrangement
17	5	3	road users	traffic lights (2)
18	6	1	conflicts	low speed (2) & digital map
19	2	6	directions & complexity (6)	digital map
20	8	1	information	rearrangement

Table 8: Encountered problems

Keyword(s)	Issue(s)
lane number	too many
direction signs	unclear
lines	broken (instead of solid)
lane markings	unclear
information	too much
bike lane	narrow or unclear
parked cars	interrupting
tram line	hard to detect
road users	too many
road sign	unclear
VRU	unpredictable conflict
complexity	too much
overview	poor
eye contact	required
priority signs	unclear or double
conflicts	too many
directions	too many

Table 9: Suggested solutions

solution(s)
low speed
digital map
no parked car
rearrangement
traffic lights

Table 10: Two way Analysis of Variance for road responses based on road attributes. Stars indicate significant factors (copy of Table 3)

Response: y (yes%) 4-factor complete model

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Function	2	0.46821	0.23410	6.6708	0.012669 *
Speed	1	0.01176	0.01176	0.3351	0.574333
Users	1	0.52501	0.52501	14.9601	0.002618 **
Type	3	0.22988	0.07663	2.1835	0.147562
Users: Type	1	0.00008	0.00008	0.0024	0.962008
Residuals	11	0.38603	0.03509		

Table 11: Two way Analysis of Variance for intersection responses based on intersection attributes

Response: y (yes%), 4-factor complete model

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Roundabout	1	0.06272	0.062720	1.0751	0.3187
Signal	1	0.00116	0.001157	0.0198	0.8902
Public transport	1	0.03138	0.031378	0.5379	0.4763
Active modes	1	0.11422	0.114224	1.9580	0.1851
Roundabout: Public transport	1	0.09758	0.097578	1.6727	0.2184
Singnal: Public transport	1	0.01265	0.012650	0.2168	0.6492
Residuals	13	0.75839	0.058337		

APPENDIX B: FIGURES

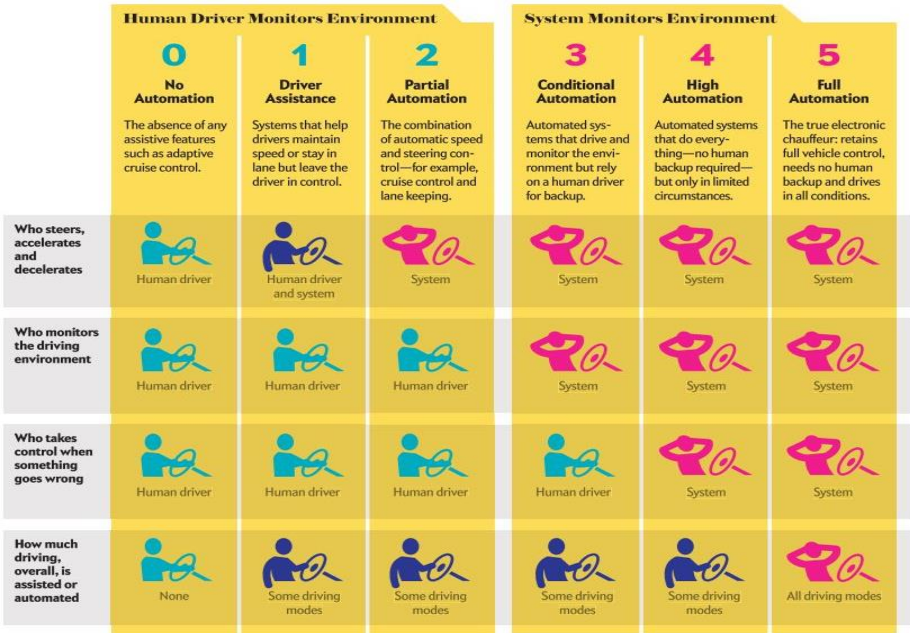


Figure 4: Levels of automation (Shladover, 2016) **(copy of Figure 1)**

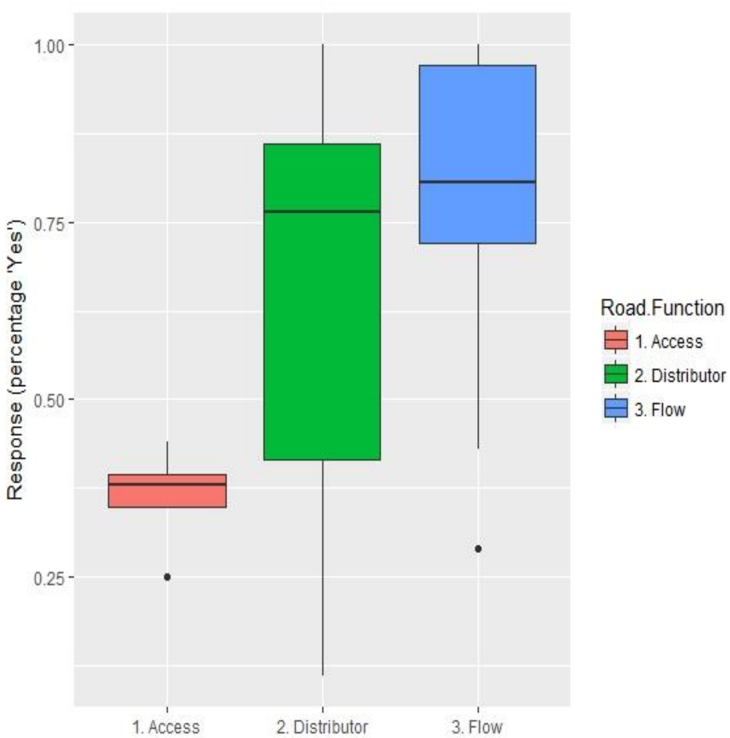


Figure 5: Response for road function categories (copy of Figure 3)

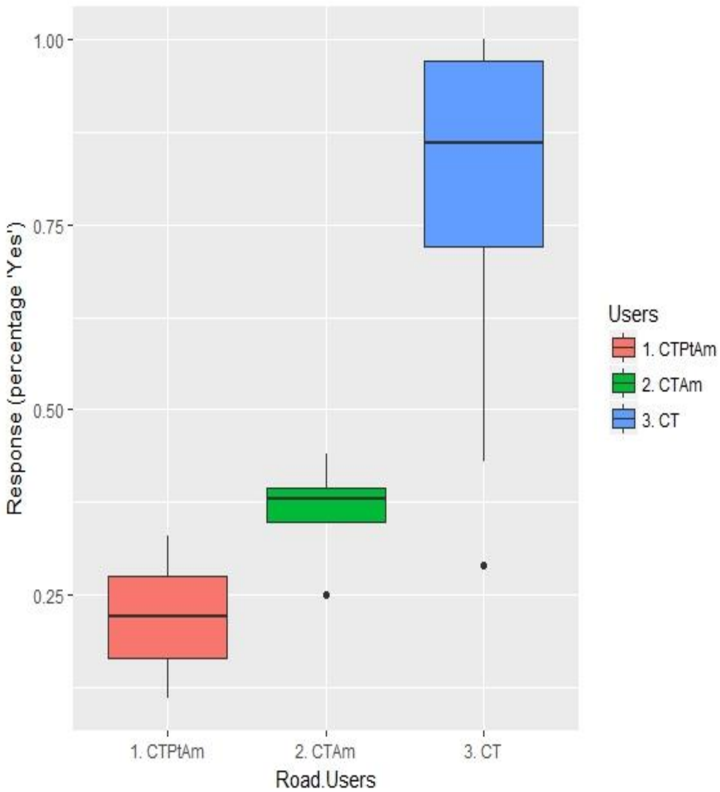


Figure 6: Response for road user categories

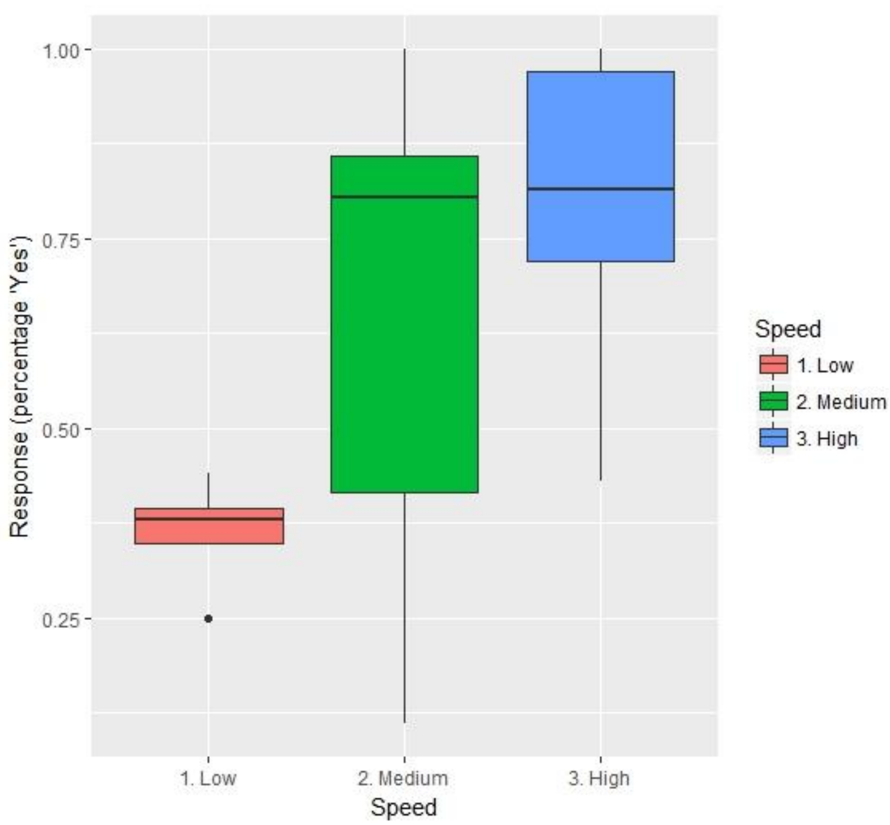


Figure 7: Response for road speed categories

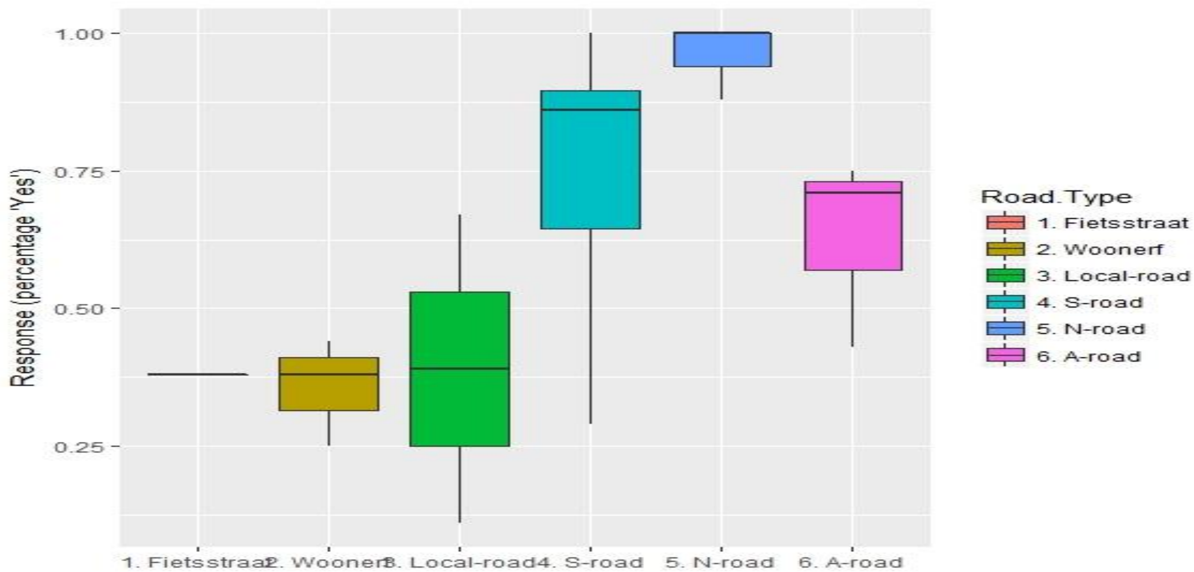


Figure 8: Response for road type categories

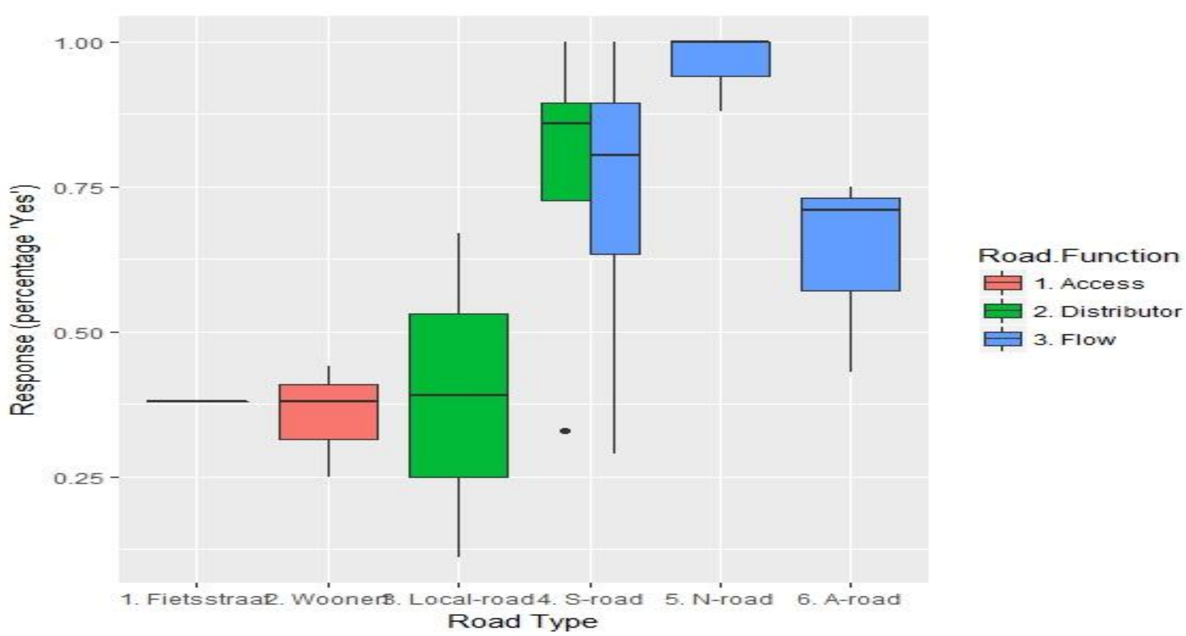


Figure 9: Response for road type categories separated based on road function

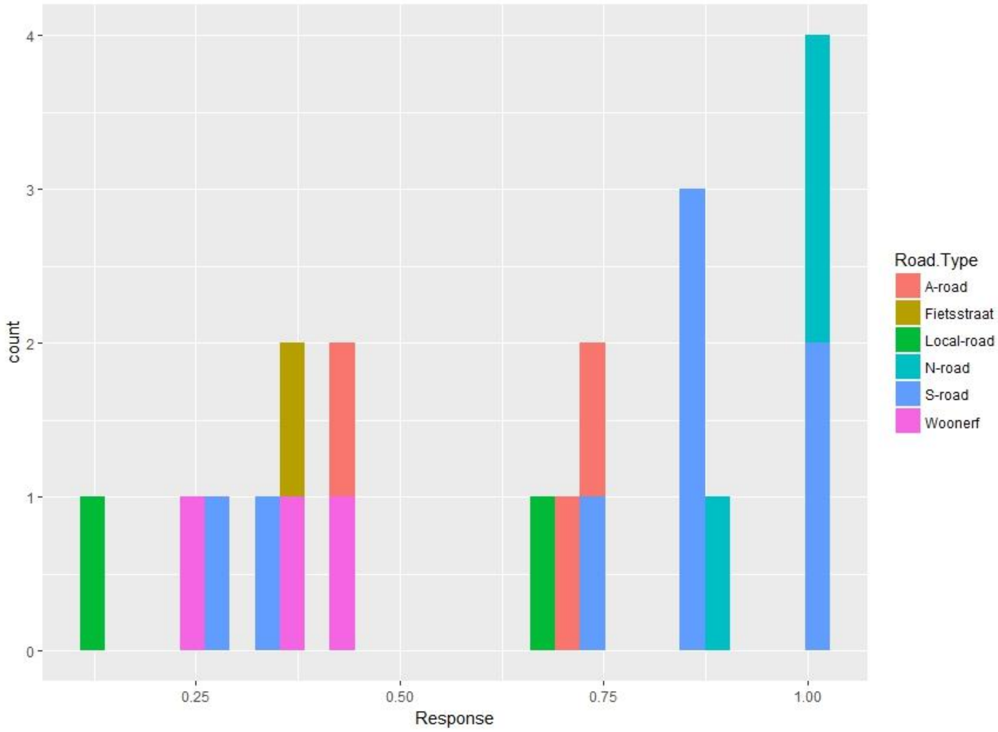


Figure 10: Response count for each road type

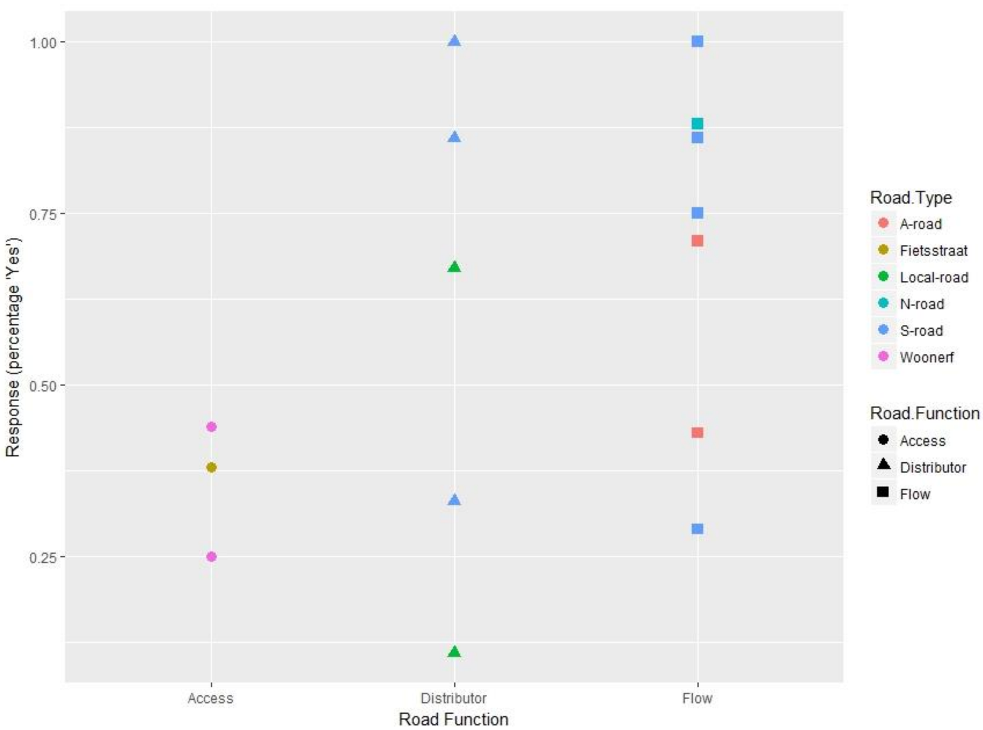


Figure 11: Response based on road function and road type

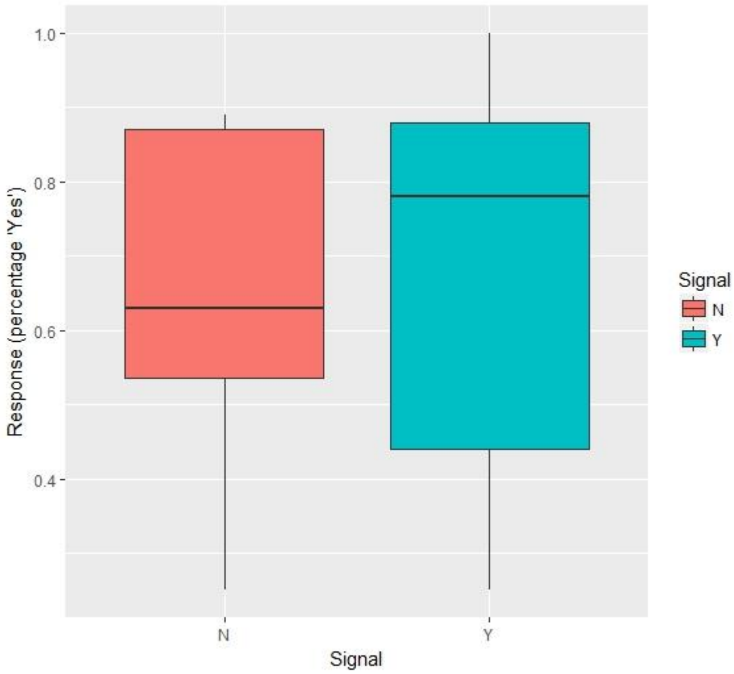


Figure 12: Responses for signalized V.S. un-signalized intersections

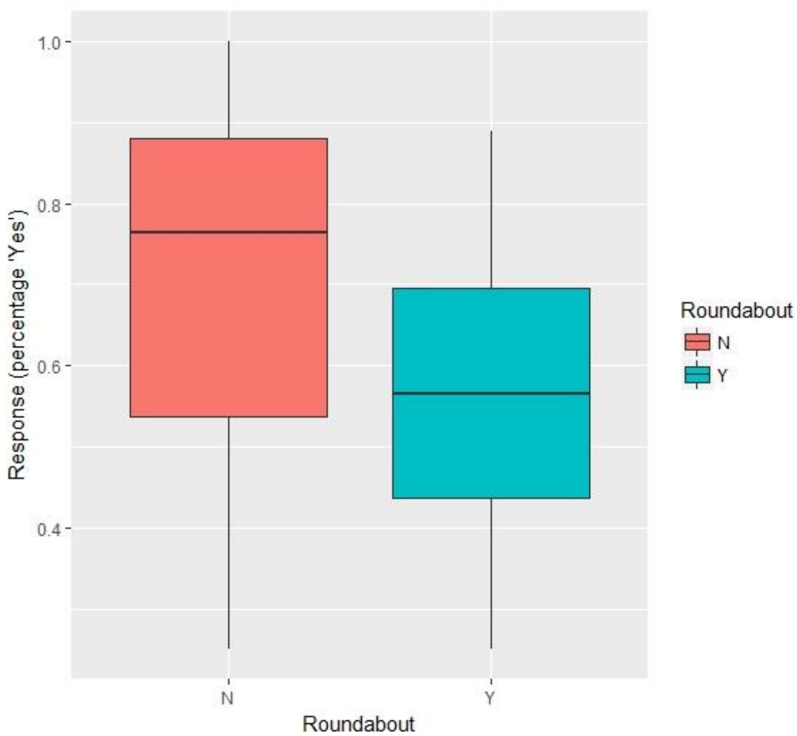


Figure 13: Responses for roundabout V.S. none-roundabout intersections

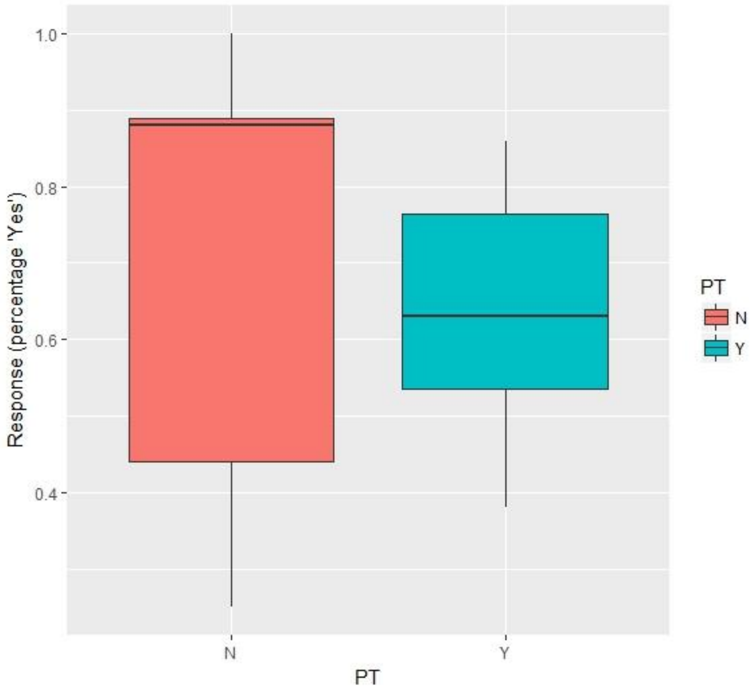


Figure 14: Responses for intersections with and without public transport

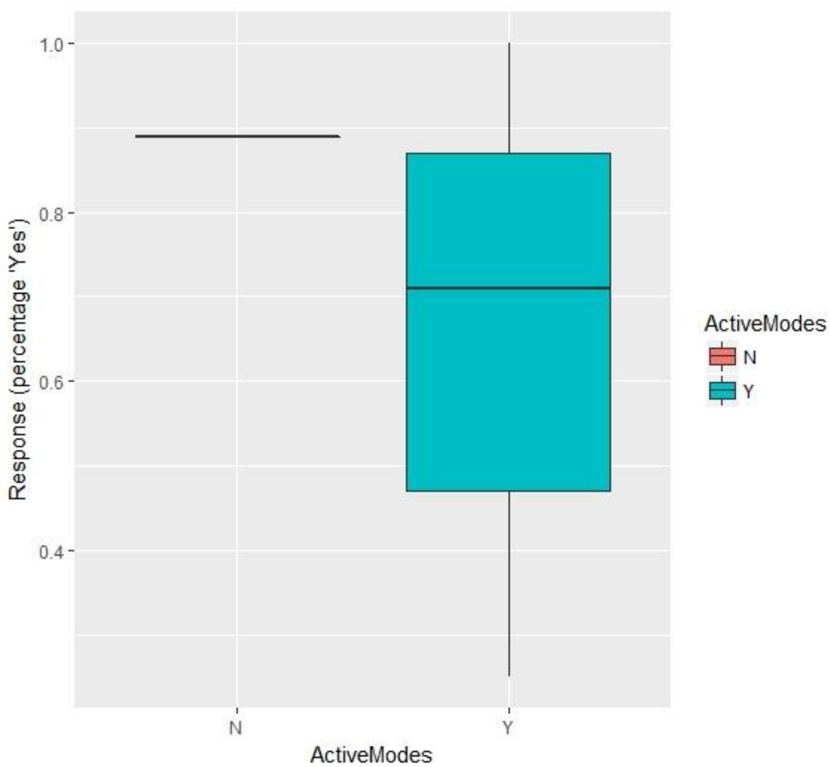


Figure 15: Responses for intersections with and without active modes

APPENDIX C: IMAGES OF ROADS

R 1

Response		Key words (issues)	Solution
YES	NO		
6	2	lane number, direction signs	-

R 2

Response		Key words (issues)	Solution
YES	NO		
5	2	lines	-

R 3

Response		Key words (issues)	Solution
YES	NO		
3	4	lane markings, information (2)	-

R 4

Response		Key words (issues)	Solution
YES	NO		
7	1	-	-

R 5

Response		Key words (issues)	Solution
YES	NO		
7	0	-	-

R 6

Response		Key words (issues)	Solution
YES	NO		
7	0	-	-

R 7

Response		Key words (issues)	Solution
YES	NO		
6	1	lane markings	-

R 8

Response		Key words (issues)	Solution
YES	NO		
3	6	bike lane (2), tram line, road users	low speed

R 9

Response		Key words (issues)	Solution
YES	NO		
6	1	parked cars (3)	-

R 10

Response		Key words (issues)	Solution
YES	NO		
9	0	-	-

R 11

Response		Key words (issues)	Solution
YES	NO		
6	2	unpredictable conflict	-

R 12

Response		Key words (issues)	Solution
YES	NO		
8	0	-	-

R 13

Response		Key words (issues)	Solution
YES	NO		
6	1	road sign	-

R 14

Response		Key words (issues)	Solution
YES	NO		
2	5	VRU (3)	low speed & digital map

R 15

Response		Key words (issues)	Solution
YES	NO		
6	3	VRU (2)	digital map & no parked car

R 16

Response		Key words (issues)	Solution
YES	NO		
1	8	road users (2), complexity (2)	-

R 17

Response		Key words (issues)	Solution
YES	NO		
4	5	VRU, parked cars	low speed

R 18

Response		Key words (issues)	Solution
YES	NO		
2	6	VRU, complexity, overview	low speed

R 19

Response		Key words (issues)	Solution
YES	NO		
3	5	VRU	low speed

R 20

Response		Key words (issues)	Solution
YES	NO		
3	5	lane markings (2), VRU	low speed

APPENDIX D: IMAGES OF INTERSECTIONS

i 1

Response		Key words (issues)	Solution
YES	NO		
2	6	lane marking (4), road users (2)	-

i 2

Response		Key words (issues)	Solution
YES	NO		
5	5	road users (3), eye contact	-

i 3

Response		Key words (issues)	Solution
YES	NO		
8	1	eye contact	-

i 4

Response		Key words (issues)	Solution
YES	NO		
5	3	priority signs, bike lane, conflicts	-

i 5

Response		Key words (issues)	Solution
YES	NO		
4	5	directions (5)	-

i 6

Response		Key words (issues)	Solution
YES	NO		
8	0	-	-

i 7

Response		Key words (issues)	Solution
YES	NO		
6	2	directions, road users, VRU	low speed (2)

i 8

Response		Key words (issues)	Solution
YES	NO		
6	1	lane marking	digital map (2)

i 9

Response		Key words (issues)	Solution
YES	NO		
4	5	VRU (4)	-

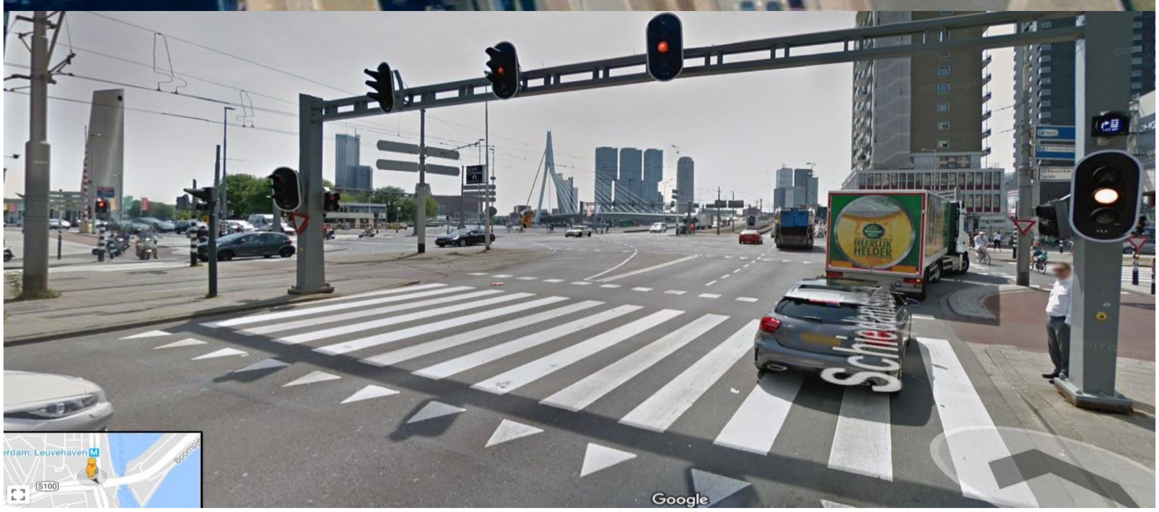
i 10

Response		Key words (issues)	Solution
YES	NO		
5	2	tram lines (2)	traffic lights (2)

i 11

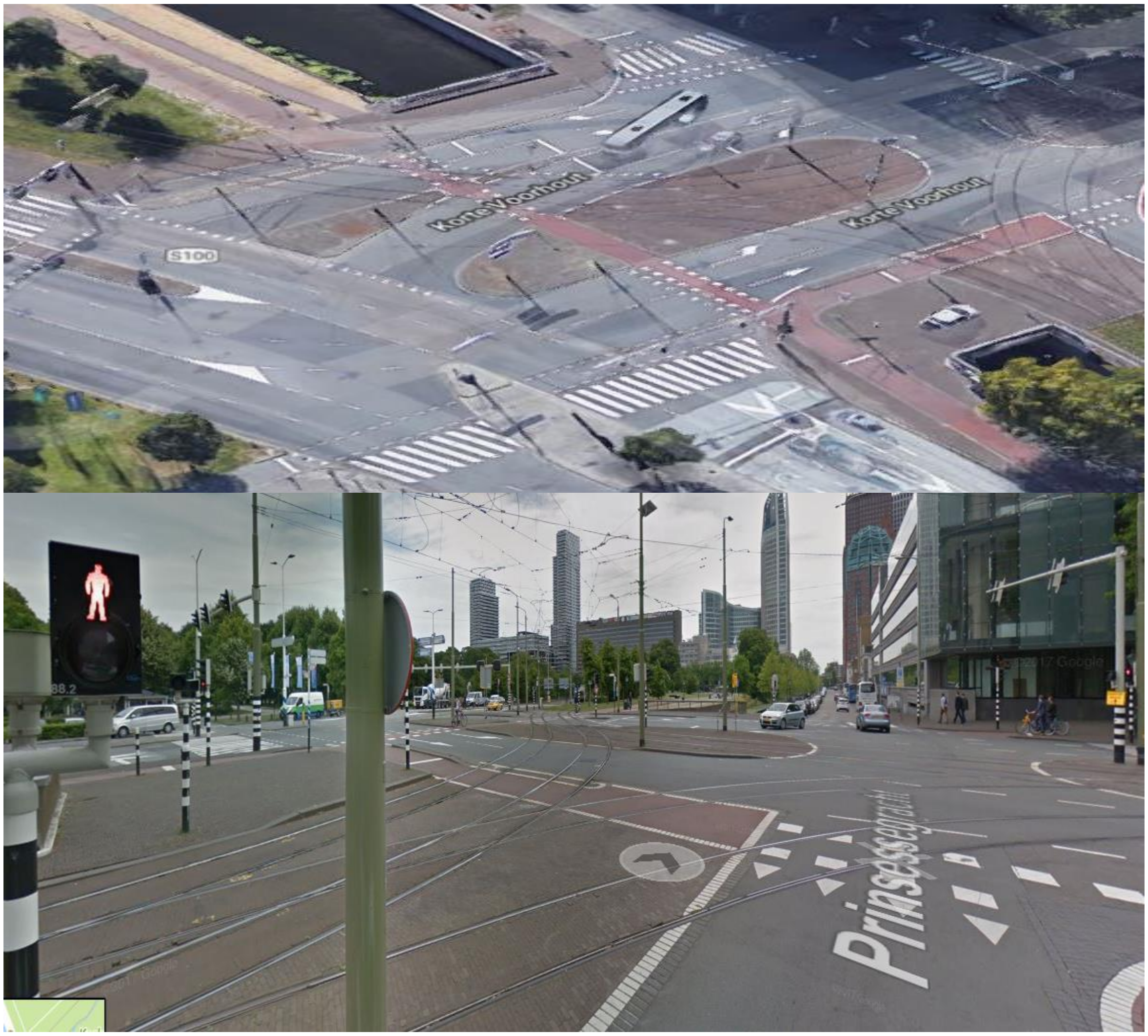
Response		Key words (issues)	Solution
YES	NO		
7	0	-	-

i 12



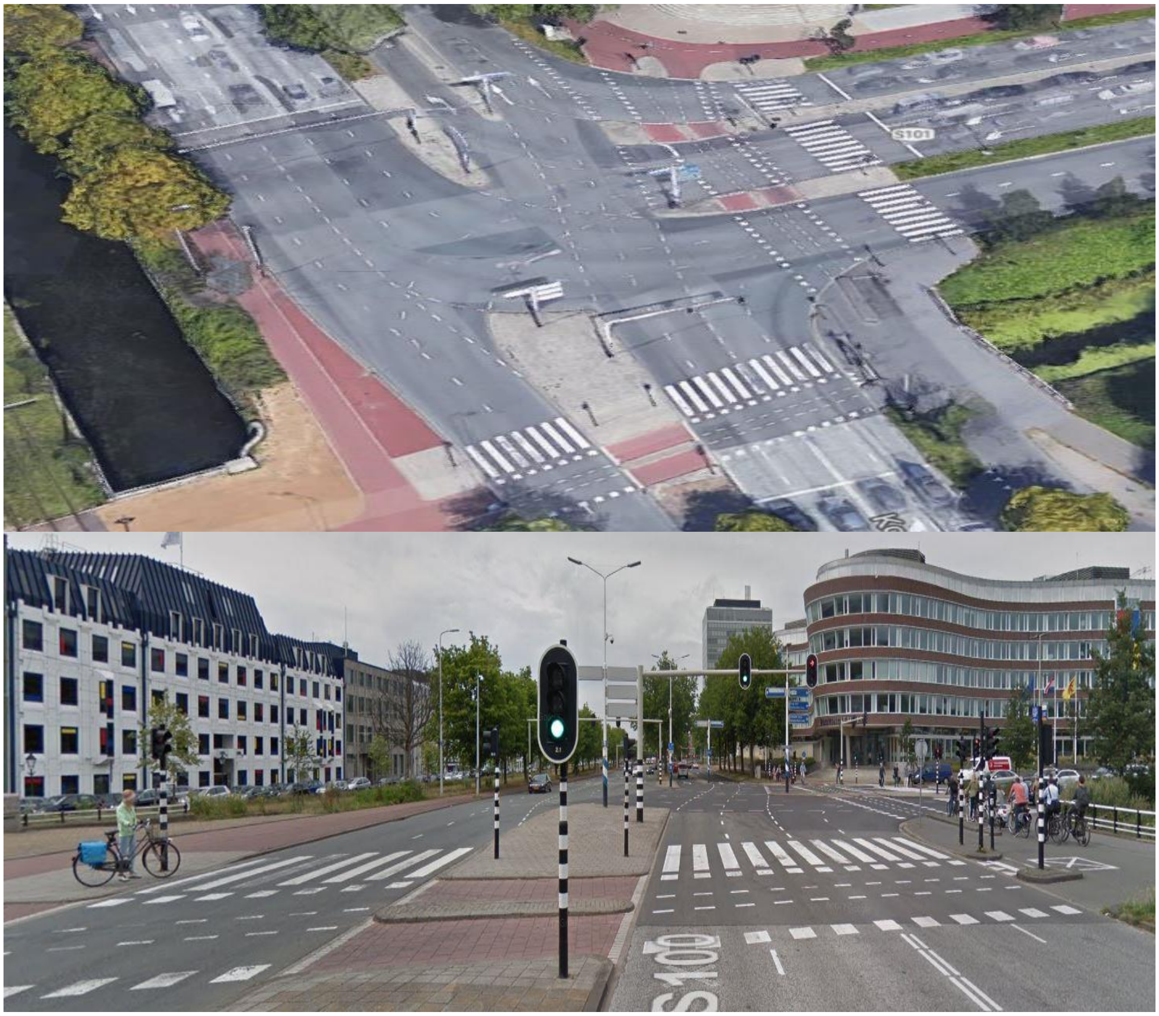
Response		Key words (issues)	Solution
YES	NO		
7	2	lane marking, complexity	-

i 13



Response		Key words (issues)	Solution
YES	NO		
3	5	VRU (2), conflicts, complexity	digital maps, traffic lights

i 14



Response		Key words (issues)	Solution
YES	NO		
7	1	bike lane	-

i 15

Response		Key words (issues)	Solution
YES	NO		
7	1	eye contact	low speed (3)

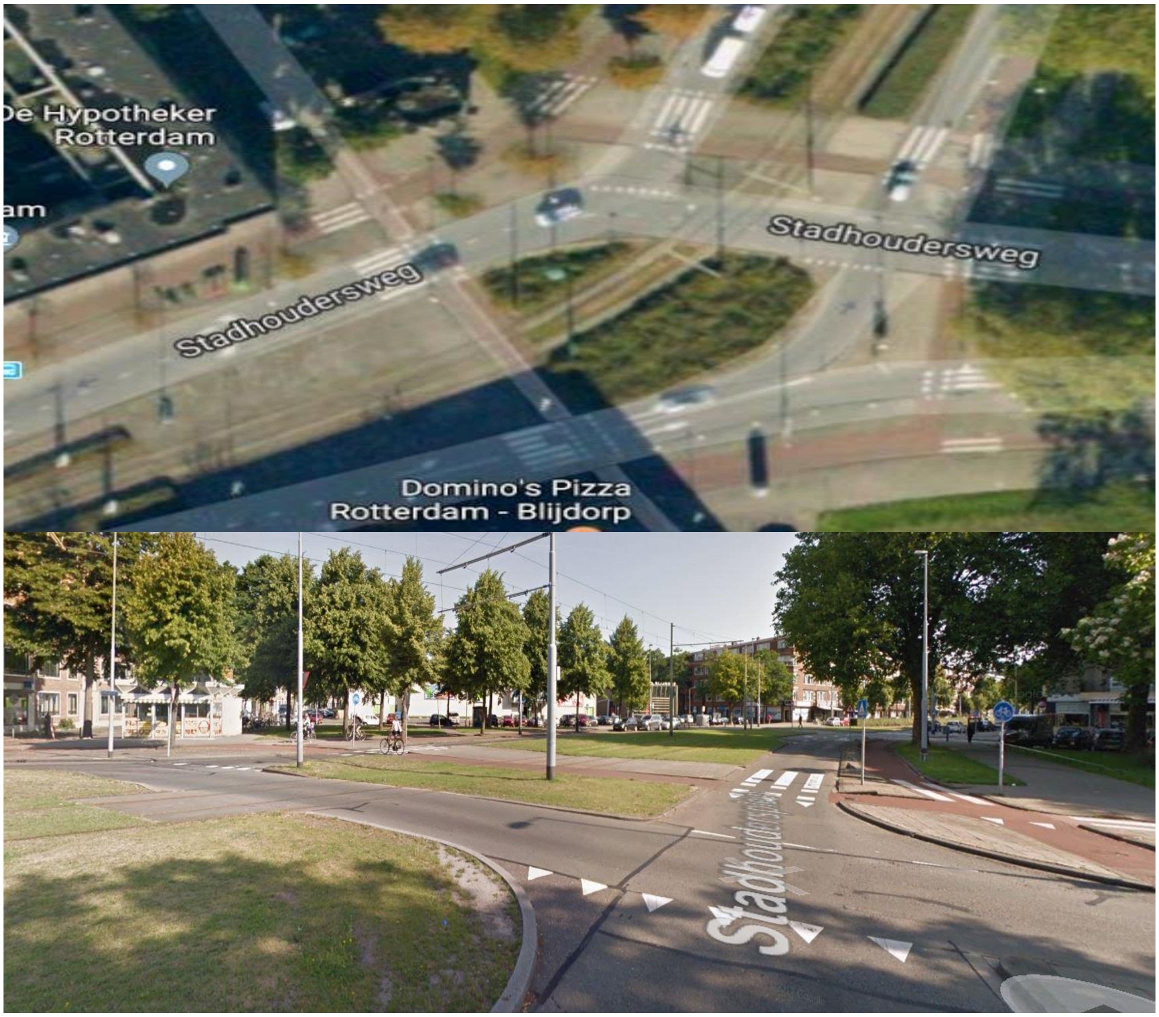
i 16

Response		Key words (issues)	Solution
YES	NO		
4	3	tram line, road users	traffic lights & rearrangement

i 17

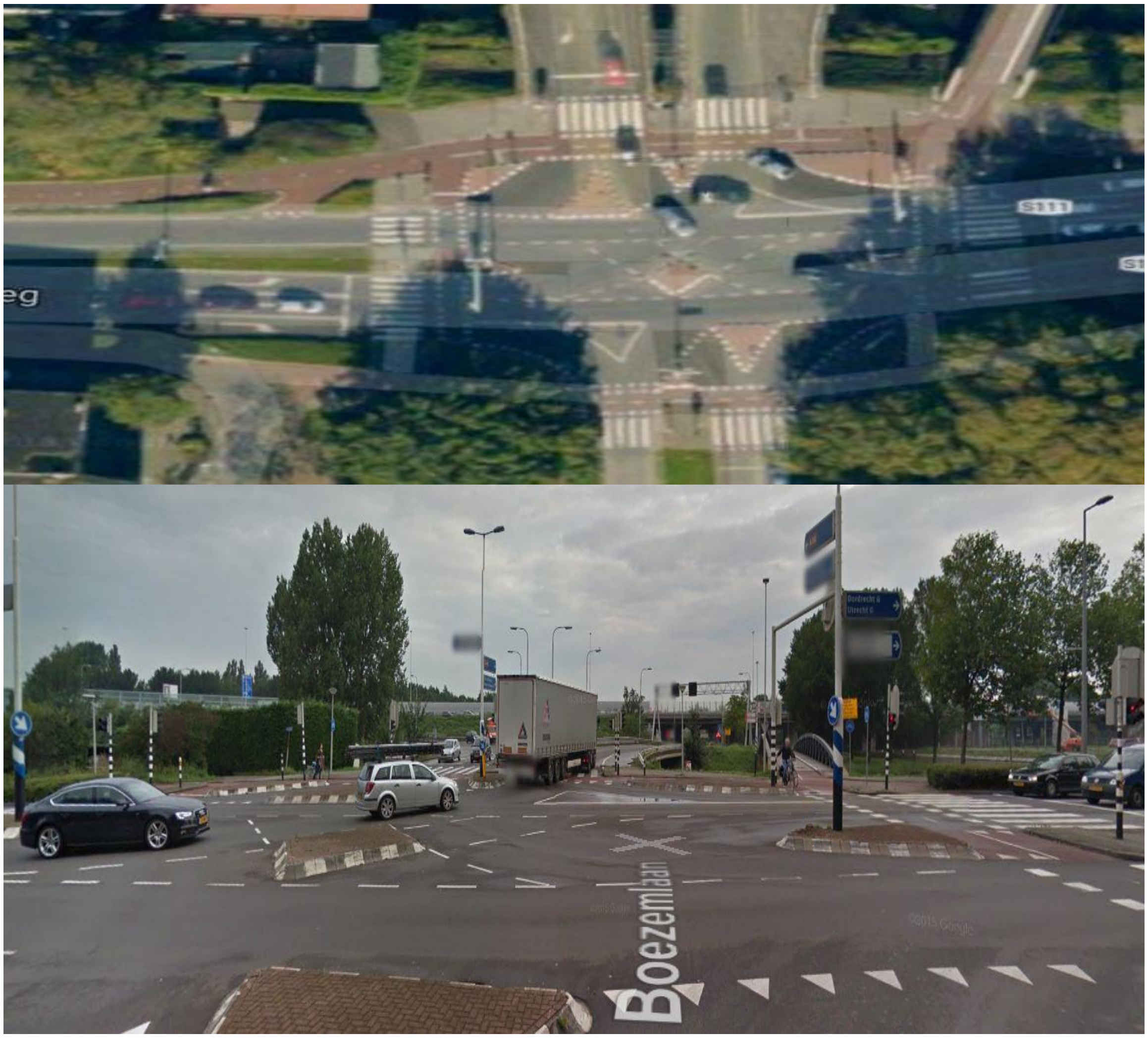
Response		Key words (issues)	Solution
YES	NO		
5	3	road users	traffic lights (2)

i 18



Response		Key words (issues)	Solution
YES	NO		
6	1	conflicts	low speed (2) & digital map

i 19



Response		Key words (issues)	Solution
YES	NO		
2	6	directions & complexity (6)	digital map

i 20

Response		Key words (issues)	Solution
YES	NO		
8	1	information	rearrangement