Bicycle safety before and after the redesign of intersections in The Hague

Assessment using automated traffic analysis software

R-2021-4A

SWOV

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Prevent crashes
Reduce injuries
Save lives

Report documentation

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Contents of the project: Video data from roads, highways and intersections can provide detailed insight on traffic flow, road user behaviour and safety. In this study, video data was collected at two intersections before and after infrastructural changes were implemented. Automated traffic analysis software was used on these data to perform traffic counts, and the logging of vehicle trajectories and safety critical events. Five video analysis tools were compared. One of the tools was used to evaluate bicycle safety before and after the intersections' redesign, by analysing the number of conflicts ('near-misses') over exposure.

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Summary

Given the recent developments in video analysis techniques, the application of these methods to the field of transportation has gained popularity. The collection of video data from roads, highways and intersections can provide detailed insight on traffic flow, road user behaviour and safety. Analysing the detailed information from the videos, would have previously required manual observers to perform traffic counts, logging of vehicle trajectories and safety critical events. More recently automated methods using computer vision techniques can potentially provide these results. The process of identifying different objects in a two-dimensional image space has been steadily improving over the years. However, they are not yet at a stage where all objects can be identified, and correctly classified.

In this study, the first objective is to evaluate whether the automated traffic analysis software are accurate enough to perform the analysis and produces results that are sufficiently reliable. Five companies were identified, and a basic comparison was conducted by providing each company sample video data that was collected in collaboration with The Hague municipality at intersections where infrastructural changes were implemented. The company with the highest performance and relevant results was selected to perform a full before-after analysis on the two redesigned intersections.

The second objective focuses on the infrastructural changes made to the intersections and the evaluation of whether or not safety was improved due to these changes. The intersection improvements are part of a project of improving road safety in the city of The Hague, where considerable attention has been paid to improving cycling safety. The two intersections are located in central The Hague. Infrastructural upgrades include implementing new dedicated cycling facilities on approaches where they did not previously exist, providing a left turning space for cyclists away from the centre of the intersection where it was previously located. Changing the traffic light green phase to provide a dedicated left turn phase for vehicles, implementing small islands to keep a distance between cars and cyclists, etc. Video data was collected for seven days from the before and after redesign, and automated methods were applied to evaluate the safety changes at the intersections using the surrogate safety measure Post-Encroachment Time (PET).

Results regarding the first objective indicate that the existing automated traffic analysis software still needs some manual input and checks to improve accuracy. Combining the manual and automated techniques relays more reliable results when evaluating car detection and tracking, whereas cyclist detection is still not fully satisfactory. There is still work needed to be done in the field of improving these automated traffic analysis tools.

Once the most reliable traffic analysis tool was applied to the set of video data, the safety results from PET (between 0 and 2 seconds) and risk (number of conflicts over exposure) indicators show that the infrastructural and traffic light phase changes were effective in improving safety at these intersections.

Contents

1 Introduction

Road traffic crashes account for approximately 1.35 million deaths each year (WHO, 2020), making road safety a topic of high priority. In the Netherlands, road deaths accounted for 661 fatalities and 21,400 serious road injuries in 2019 (SWOV, 2020a; 2020b).

Reducing the number of road deaths and injuries has been a focus of many European countries, with the well-known ”Vision Zero” plan aiming towards no deaths and serious injuries on European roads by 2050 (European Commission, 2019). In order to achieve this, an understanding of where and why road accidents happen is required. Reducing the number and severity of road accidents relies on the factors that lead up to the accident, and testing of alternative methods to identify those that yield to the best improvement in safety.

Cyclists, as vulnerable road users are at a much higher risk of injury and fatality when involved in a road accident. In the Netherlands, crashes involving cyclists account 31% of road deaths and vehicle deaths account for 36%, indicating the dangers of cycling (SWOV, 2020a). Studies have identified urban intersections as one of the hotspots for traffic accidents and casualties (Dozza, 2017; Jensen, 2000; Schepers et al., 2013, 2015; Teschke et al., 2012). In the Netherlands 64% of cyclist fatalities happen in urban areas and 60% of these occur at intersections (SWOV, 2021). Several studies have evaluated the safety of cyclists at intersections, identifying specific infrastructural components (lack of a cycling facility), geometric design (sharp turns), and interacting manoeuvre (right turning and through conflicts) which increase the risk of a cyclist accident. Cyclist safety has been shown to be at a higher risk when there is the possibility to perform several different manoeuvre, since drivers cannot expect and predict the cyclist movements from all directions (Gerstenberger, 2015; Herslund & Jørgensen, 2003; Nabavi Niaki et al. 2019).

Methods of analysing road safety have evolved over the years. Past studies relied on historical accident data. However, there are several issues with this approach. The first problem is underreporting of accidents and the lack of detail of the situation that lead to the accident, the second issue is the limited number of accidents happening at a single location over the course of several years (Alsop & Langley, 2001; Amoros, Martin & Laumon, 2006). The safety analysis at these locations could be based on outdated information since over the years there could have been several changes to the infrastructural, behavioural and traffic flow influencers at that location.

More recent studies have taken a proactive approach, not waiting for accidents to happen in order to prevent them, which is more ethical and provides information on the situations that could lead up to the accident. This method makes use of surrogate safety measures which identifies dangerous road incidents that do not lead to an accident but their frequency and severity can be used as a safety indicator (further details of this method are described in the Background section).

In summary, investigation of safety at intersections, as accident hotspots, using surrogate safety measures, provides the insights needed to make improvements to road safety. This approach is helpful when improving the safety of certain locations or when planning a redesign, it can also be used to perform before-after studies to evaluate the safety improvement at redesigned locations.

In the municipality of The Hague, two intersections deemed unsafe underwent a minor and major infrastructural update. To evaluate the safety changes caused by the redesign, surrogate safety measure methods are adopted to compare the before-after safety at the two intersections.

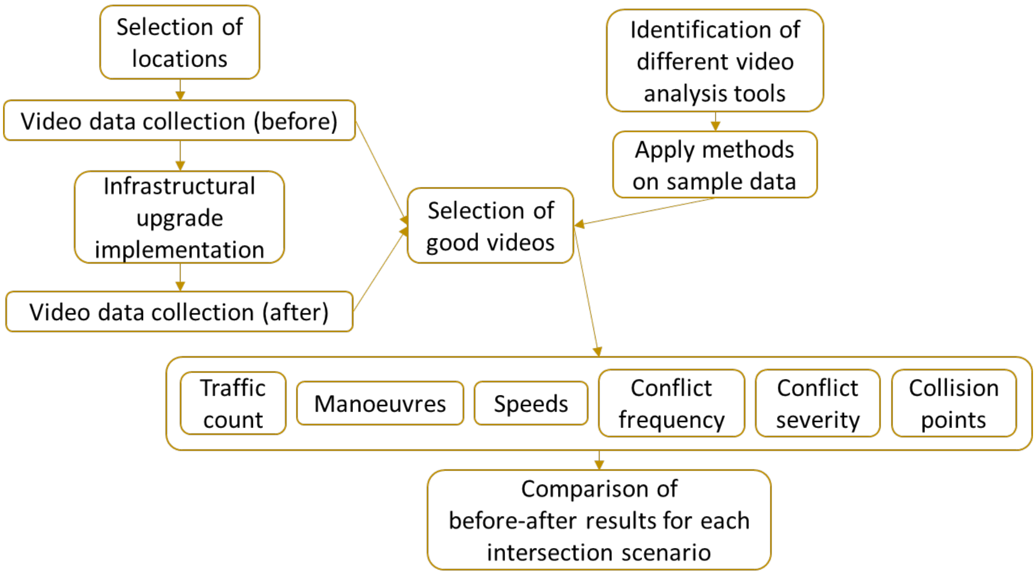
1.1 Study Objectives

In collaboration with The Hague municipality, SWOV performed two before-after studies at intersections where infrastructural changes were implemented aiming to improve safety. The intersection improvements are part of a project of improving road safety in the city of The Hague, where considerable attention has been paid to improving cycling safety. The aims of this project are to:

- Evaluate whether automated traffic analysis software are accurate enough to perform safety analysis and produces results that are sufficiently reliable;
- Evaluate the safety changes of infrastructural redesign at two intersections in The Hague.

2 Methodology

In this section, the methodology for the objectives of this study are presented. The first is to identify available video analysis tools, and the second is to apply the method to the video data collected from the two The Hague intersections to evaluate the effects of infrastructural changes on safety.



2.1 Background on Surrogate Safety Measures

2.1.1 Safety Pyramid

Figure 2.1 shows the safety pyramid developed by Hydén (1987). The base of the pyramid indicates the events with the highest frequency gradually reducing in frequency moving up the pyramid. Undisrupted traffic passages account for the majority of the road traffic condition. The next level up are traffic conflicts which are events that may lead to an accident if an evasive action is not taken. These can be divided into potential conflicts, slight conflicts and serious conflicts. These events happen more frequently than crashes which are only at the top of the pyramid, where the least frequent events are accidents with injuries and fatalities. Studying traffic conflicts has provided insight into why and how crashes occur without the need for crashes to occur, as it represents the proximity to crash occurrence. The benefits of this approach include their higher frequency, proactive nature, and the shorter duration of time that needs to be studied (Hydén, 1987; Kraay & Van der Horst, 1985; Sayed & Zein, 1999).

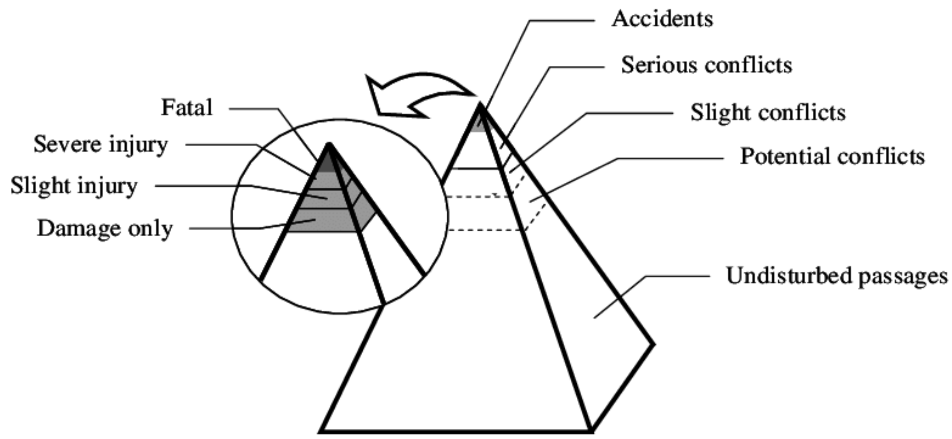


Figure 2.1. Safety Pyramid (Hydén, 1987)

2.1.2 Traffic Conflicts

Conflicts occur when two road users interact with each other in time and space, where a potential collision point can exist. Surrogate safety measures are indicators that represent conflicts as safety-critical events. Several surrogate safety measures exist to identify the number and severity of conflicts. *Figure 2.2* represents a through travelling road user (in red), and its potential collision points with road users travelling on the road.

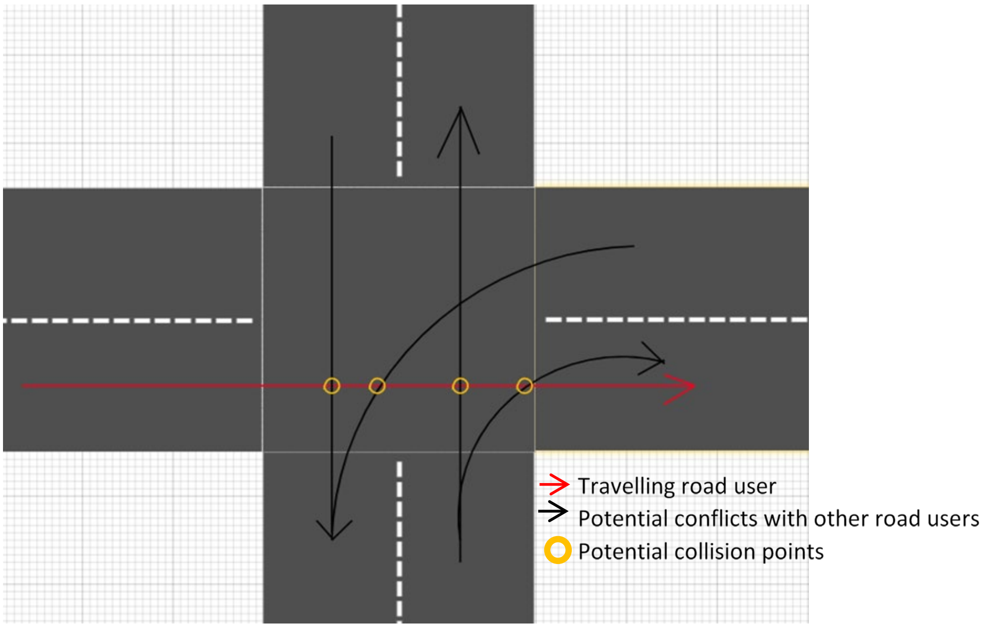


Figure 2.2. Road user conflicts and potential collision points

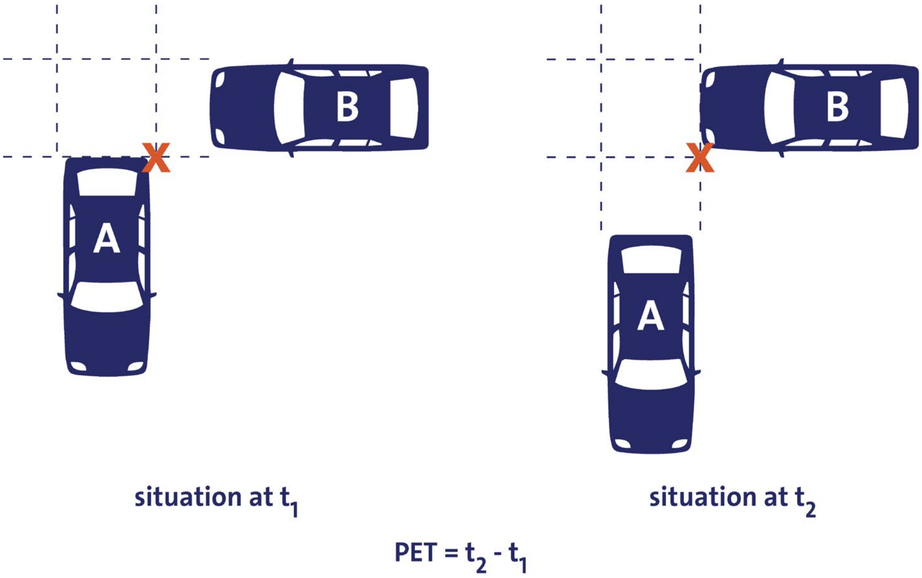
2.1.3 Surrogate Safety Measures

Surrogate safety measures identify conflicts, collision points and the severity of the conflicts. One of the most common surrogate safety measures in literature is post-encroachment time (PET).

2.1.3.1 Post-Encroachment Time

PET indicates the time it takes for the first road user to exit the collision point (**X**) and the next road user to enter it (*Figure 2.3*). If PET is zero, then the two road users have collided. Therefore, lower PET values indicate more severe conflicts, and a higher likelihood of crash occurrence. For this study we use four different categories to indicate safety, PET values between 0 and 0.5 seconds indicating very severe conflicts, values between 0.5 and 1.0 seconds as severe conflicts, PET between 1.0 and 1.5 as less severe conflicts and 1.5 to 2 seconds as not severe conflicts (Zangenehpour et al., 2016).

Figure 2.3
Post-Encroachment Time (PET)



2.1.3.2 Risk Assessment

The number of conflicts indicate the frequency of which unsafe interactions happen. An improvement in safety requires a decrease in the number of conflicts. For comparison purposes, the safety indicators of before and after are normalised using an exposure measure (such as traffic flow) as risk:

Risk = safety indicator/exposure

= number of conflicts/traffic flow in conflicting movement (product of vehicle and cyclist flow)

2.1.4 Commonly Used Variables

Several variables are commonly used in literature traffic analysis. The considered variables are compared between before and after the infrastructural changes are implemented:

- Road user trajectories
- Road user speed
- Surrogate safety measures (post-encroachment time)
- Risk: number of conflicts/traffic flow
- Collision points

Focusing on the first variable, it is important to know how the infrastructural change influenced the location and manoeuvres of the road users at the intersection. For example, is the design able to guide the cyclists to perform safer manoeuvres? The second variable is speed, if an infrastructure improvement targets speed, this variable can be used to compare the before and after effects on speed. The final variables represent safety by looking at traffic conflicts instead of historical accident data. Surrogate safety indicators can indicate the total change in number of conflicts and risk from the before to after situation. Finally, collision points indicate the location where the two road users would have collided. Safety improvement depends on different factors when looking at collision points. In general, a larger area containing collision points means more danger zones. Conflict points can highlight the change in safety due to the infrastructural change, which are useful for identifying potential danger zones at an intersection. Of the mentioned indicators, conflict frequency, severity and collision points, will be used to evaluate the change in safety from the before to the after redesign of the two locations.

2.2 Background on Video Analysis Methods

Although the identification of objects such as cars and bikes on the road are intuitive to humans, computer-based road user detection from video requires complex image processing algorithms. The process of identifying different objects in a two-dimensional image space has been steadily improving over the years. However, they are not yet at a stage where all objects can be identified, and correctly classified.

In the field of transportation, image processing has been adopted to study road user behaviour and unsafe interactions. Image processing and road user tracking has been done via two main analysis methods: feature-tracking, and object-detection. The following sections go into some detail on how each method works as well as their strengths and weaknesses.

2.2.1 Feature Tracking Method

This method identifies moving features (corners, textured areas) in the image. The unmoving background is identified and subtracted and any other feature that moves in subsequent images is tracked. In the next frame, a search window radius is selected to identify the moved feature based on the maximum motion between any two consecutive frames. *Figure 2.4* shows the identified features on two cars and one bike in the video image with a number assigned to each feature.

Figure 2.4. Identified features from two vehicles and one cyclist

In the next frames, the same features are found in addition to any new features that may have been identified and are tracked as shown in *Figure 2.5.*

Figure 2.5. Tracked features of two vehicles and one cyclist over several frames

The next step is to identify the objects, to do this, the features within a certain distance with similar speed are combined as one object as shown in *Figure 2.6.*

Figure 2.6. Combined similar features to indicate one trajectory per road user - notice that the black car has two trajectories one before the pole (red) and one after (light blue)

The final stage is classification, where the objects are categorised as cars, pedestrian and cyclists, this is done through a training set to identify similar features from the objects in the video and the image training set.

2.2.1.1 Weaknesses

Although this method is able to identify moving objects quite well, there are limitations associated with it. The first is that stopped objects cannot be identified since only moving features are detected. Therefore, if a left turning car stops in the intersection to give way to pedestrian, the tracking will stop, and start again only when the car starts moving. This is problematic when trying to track the road user's entire trajectory. Another issue which is visible in *Figure 2.5* and *Figure 2.6,* is that the light pole cuts off the tracking of the black car. This is because the stationary pole does not allow for the tracking of the features of the car passing behind it.

2.2.2 Object Detection Method

This method adopts deep learning to identify road users based on an image training set. A comprehensive set of images from cars, bikes, and pedestrian from all angles and in all shapes are used as a training set. Based on the training set images, the software is able to identify a road user that looks like a car, bike or pedestrian. Once road users are identified in an image space, the software must identify the same objects in the following frames and through other algorithms, stitch the trajectory of each road user as shown in *Figure 2.7* and *Figure 2.8*. The advantage of this method is that it is able to detect stopped objects, and if there is a pole or object partially obstructing the road user, if the training set is comprehensive enough to account for these situations, the object can still be correctly detected. Such as the black car in the top right corner of *Figure 2.7* which is partially obstructed by the pole but is still identified in the green box as a car.

Figure 2.7. Object detection of cars and cyclists (image from TNO)

Figure 2.8. Trajectory of identified car over several frames (image from TNO)

2.2.2.1 Weaknesses

One of the disadvantages associated with object detection method lies in the training set. If the training set is limited and does not cover road user images from all angles, in different light condition, and in different positions, it will miss some objects in the video. If an object is not identified in one of the frames, the trajectory cannot be stitched together to indicate the full manoeuvre. Similarly, an object can be detected incorrectly twice in the same frame (for example assigns the same object ID to two different cars), which leads to issues with stitching the trajectory together.

2.3 Application of Video Analysis Tools

To identify which method is better suited for our analysis one feature-tracking based software and four object-detection based methods from different traffic management companies were tested.

2.3.1 Traffic Intelligence – Feature Tracking

The first software that was tested was an open source tool "traffic intelligence" (Jackson et al., 2013), which uses the feature tracking approach to extract road user trajectories. Given the issues with the pole blocking the road user view from the video image as mentioned in *Section 2.2.1.1*, this method was not suitable for our situation given the poles cutting off trajectories in the intersection, and investing the time to overcome this issue was deemed costly. As a result, a search for traffic analysis software using object detection methods was carried out. This method is ideal for videos that do not have infrastructure blocking the road users' trajectory. Some technical background is required to apply this method, but the open-source nature of it makes it attractive since it is free to use and contribute to the software.

2.3.2 TNO – Object Detection

The first object detection methodology used was from a Dutch company TNO. They developed an object detection software to extract road user trajectories as a part of the Horizon 2020 project "In-depth Understanding of Accident Causation for Vulnerable Road Users" (InDeV) (TNO, 2017). Their software detects critical traffic situations in cycling crossings, analyses the trajectories of bicycles and vehicles and computes important safety indicators. The tool developed by TNO is quite promising and innovative, yet its functionality in real cycling crossings and the validity of the extracted data had not been widely checked. A sample of the video data was provided to them for analysis, and a manual validation was carried out.

Table 2.1 indicates the validation of nine videos (135 minutes) which were manually annotated for the purpose of accuracy evaluation. The table indicates the number of objects, which were either double detected in one frame or not detected in one or more consecutive frames, to be between 708 and 1340 in one quarter of one hour. In addition, in the data of two videos, there are more than 241 objects with velocities higher than 150 km/h. This value is quite unusual in an urban intersection with traffic lights.

Table 2.1. Statistics on the results

Video date and time	Double Detected Objects or Objects with Missing Frames	Objects with Speed > 150 km/h	Number of bicycles
22-10:30	708 (91.1%)	0 (0.0%)	20 (2.6%)
22-18:00	1015 (97.3%)	77 (7.4%)	10 (1.9%)
23-16:30	1243 (95.0%)	164 (12.5%)	48 (1.5%)
24-08:15	1118 (95.4%)	0 (0.0%)	68 (1.7%)
24-08:30	943 (93.1%)	0 (0.0%)	62 (2.0%)
24-10:15	732 (95.4%)	0 (0.0%)	62 (2.6%)
24-16:30	1340 (92.3%)	0 (0.0%)	45 (1.4%)
24-18:00	977 (95.9%)	0 (0.0%)	48 (2.0%)
25-14:00	1180 (91.9%)	0 (0.0%)	49 (1.6%)

Furthermore, the maximum percentage of bicycles passed from the study intersection, according to the trajectories, is equal to 2.6%. Hence, the detection function of the TNO application was not able to correctly localize the cyclists. The performance of the tracking function was not accurate for the purposes of this study. As indicated above, the results obtained from TNO were not satisfactory. After several months of back and forth of evaluation of their tool, giving suggestions, and re-evaluating updated versions, it appeared that the software was not yet at a stage to produce results for our purposes. Steps were then taken to identify other options for the data analysis.

2.3.3 Data from Sky – Object Detection

The second option was an international company, "Data from Sky". They also adopt an object detection method; however, their software is calibrated for video data collected only from a top view. Since our video data was collected at an angle, our expectations of the software for our specific study were not high. We provided them with a sample of the same nine videos as TNO. Looking through the results, in addition to the low tracking quality due to the camera angle, they could not perform any safety analysis, and could not provide us with the trajectory data for us to perform safety analysis ourselves. In general, their analysis of a sample of our video data was not accurate. Further validation was not performed as was for TNO because the quality of the data was clearly insufficient.

2.3.4 Brisk Synergies – Object Detection

The third option was another international company "Brisk Synergies" who perform traffic behaviour and safety analysis based on object detection methods and surrogate safety measures. Given their background in projects similar to ours, they were able to provide us with personalized results for trajectories and safety. A sample of the video were sent to them, and after several checks, they were able to improve their detection quality which was not ideal in the first test level especially for cyclists. After improvements to their software and training set, they were able to provide an acceptable quality of trajectories and safety indicators. They also provided PET values as the conflict severity indicator.

A validation of the Brisk Synergies method was carried out. Two before and two after videos were selected and manually annotated. The results from the software were crosschecked with the manual counts to identify the accuracy in road user detection. The table below indicates the results of the manual count and Brisk detection at two different times, one (Time 1) is at 8:30 in the morning and the other (Time 2) at 16:45 in the after scenario.

Table 2.2. Road user Detection Performance from Brisk Synergies

		Manual count	Brisk Synergies Count	Deviation from manual counts
Vehicles	Time 1	181	185	2 %
	Time 2	256	236	- 8 %
Total deviation from vehicle detection				3 % under-estimated
Cyclists	Time 1	54	85	57 %
	Time 2	95	109	15 %
Total deviation from cyclist detection				36 % over-estimated

The results indicate an overall 36% deviation in detection performance for cyclists (over-estimation) and -3% cars (under-estimation). The variation in detection performance could be due to the time of day that is getting dark, and the time that is raining. In general, vehicles are detected with a higher accuracy compared to cyclists.

2.3.5 Mobycon – Object Detection

The final option is Mobycon which utilizes an external company MicroTraffic to perform video analysis. An object detection method is used which adopts a convolutional neural network, trained on large datasets to identify and classify road users. A sample of the video were sent to them to check traffic count performance.

Table 2.3. Road user Detection Performance from Mobycon

		Manual count	Brisk Synergies Count	Deviation from manual counts
Vehicles	Time 1	181	183	1 %
	Time 2	256	259	1 %
Total deviation from vehicle detection				1 % over-estimated

Detection results indicate a high accuracy for vehicle detection 1%. However, their cyclist detection results are not indicated in the table since their method relied on the counting a cyclist twice if they travel through two crossings resulting in over-estimation of cyclists by 93 %. Furthermore, they provide safety analysis (Appendix A), however, our team reached out to Mobycon closer to the end of the project where time and budget limits did not allow for a full comparison analysis of the intersections by Mobycon.

2.3.6 Selected Method

Based on the results presented in this section, Brisk synergies was chosen to perform a deeper analysis of the before after scenarios.

2.4 Intersection Infrastructural Changes

The two intersections in The Hague that have undergone several infrastructural improvements are:

- Jonckbloetplein: De Genestetlaan & Goeverneurlaan
- Alkemadelaan: Van Alkemadelaan & Wassenaarseweg

The general infrastructural improvements at the Jonckbloetplein and Alkemadelaan intersections are described below.

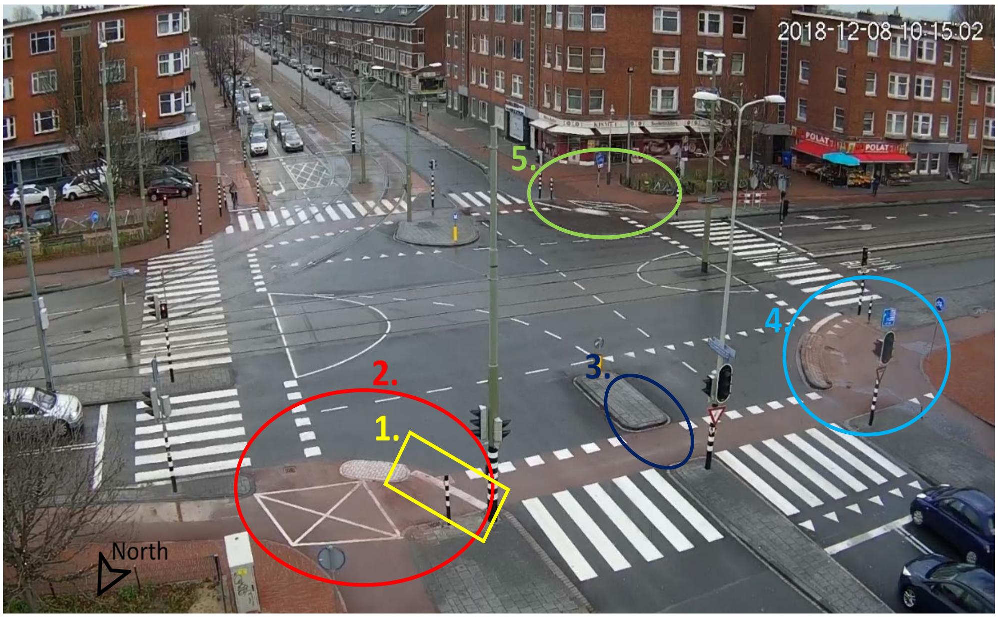
2.4.1 Jonckbloetplein

The intersection of De Genestetlaan & Goeverneurlaan is a major intersection in the south of The Hague, located at a mixed used area of residential and commercial land use with shops and restaurants. There are two tramlines going through the intersection, and there are dedicated cycling facilities on all four approaches. There is high traffic flow through the intersection from all approaches as it connects south The Hague to the centre, and is the main connecting road of east to west in the area. The speed limit on all approaches is 50 km/hr and the traffic composition is a mix of cars, vans, trucks, motor cycles, scooters, bikes and pedestrian as well as trams. The traffic light phase allows for simultaneous green for both cyclists and cars in certain directions.

Some of the infrastructural changes especially to the cycling facility are indicated in *Figure 2.9* and *Figure 2.10*. Starting from number 1. (yellow box), the cycling stop line has been moved closer to the intersection in the after scenario. This was done with the aim to have cyclists stop at a location where they are more visible to right turning cars. Circle number 2. (in red) highlights the small raised island at the intersection separating cyclists from traffic and providing them with more space to stop at the line in the after scenario. Cyclists traveling through to the other side of the intersection previously had to travel close to traffic, as indicated in circle 3. (navy circle), in the after scenario however, the dedicated cycling space has been shifted more towards the inside of the road and away from the traffic on the intersection with a small raised separating island. A similar raised island is shown in circle 2, 4, and 5. (green) in the after scenario with more space for cyclists to stop and manoeuvre through.

Figure 2.9 Intersection design before improvements

Figure 2.10 Intersection design after improvements



2.4.2 Alkemadelaan

Van Alkemadelaan & Wassenaarseweg is the intersection of two distributor roads. It is located in a residential area, with high traffic volumes from road users traveling to and from the city centre towards east The Hague. Originally only half the approaches had a dedicated cycling facility. There is a bus line running on the Van Alkemadelaan. Right and left turns are allowed from all approaches, with the exception of right turns from the north-west approach only in the before scenario.

Figure 2.11 and *Figure 2.12* indicate some of the infrastructural changes to the Alkemadelaan intersection specifically aimed at improving the cycling network. The first change is the location dedicated for cyclists making a left turn in the before scenario indicated as box 1. (yellow). In the before scenario, left turning cyclist had to stop in this area next to travelling cars and proceed to the Wassenaarseweg when the traffic light was red in the northbound Van Alkemadelaan direction. This has been replaced by a dedicated cycle lane further away from the intersection providing more space for cyclists to stop in circle 2. (red). In addition to that, the four corners of the intersection had only one dedicated cycling space in the before scenario which was changed in the after scenario, shown in circles 2. (red), 4. (light blue), 5. (green), and 6. (black). Traveling between these corners, there is an added dedicated space along the crossing of each approach in the after scenario indicated in box 1. (yellow), and circle 3. (navy) in the after scenario (*Figure 2.12*). Finally, box 7. (orange), shows the cycle path located between the through and right/left turning vehicle lanes in the before scenario, where cyclists had to travel through the middle of the intersection, this is changed after the redesign to dedicated space for cyclists along the right side of the road.

Figure 2.11 Alkemadelaan intersection before improvements

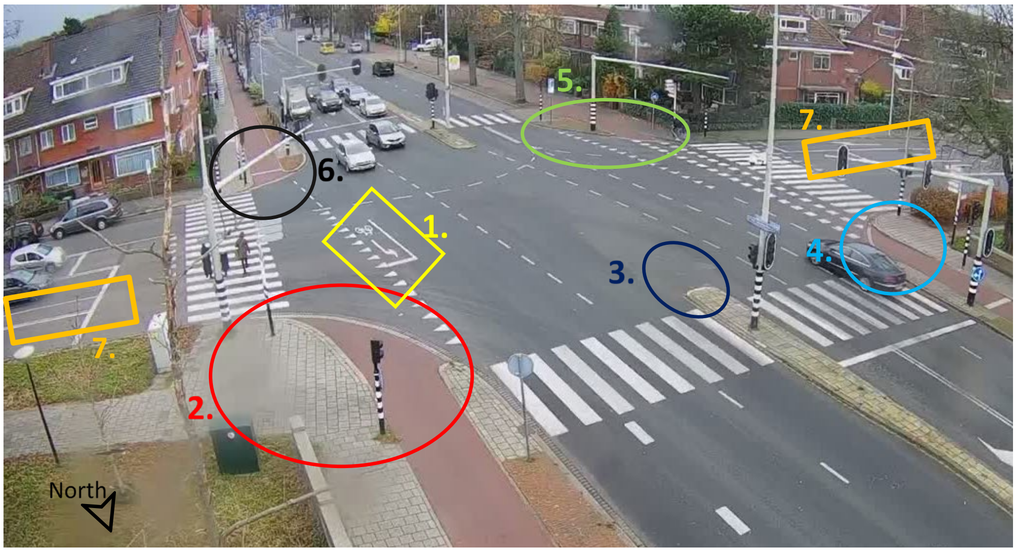
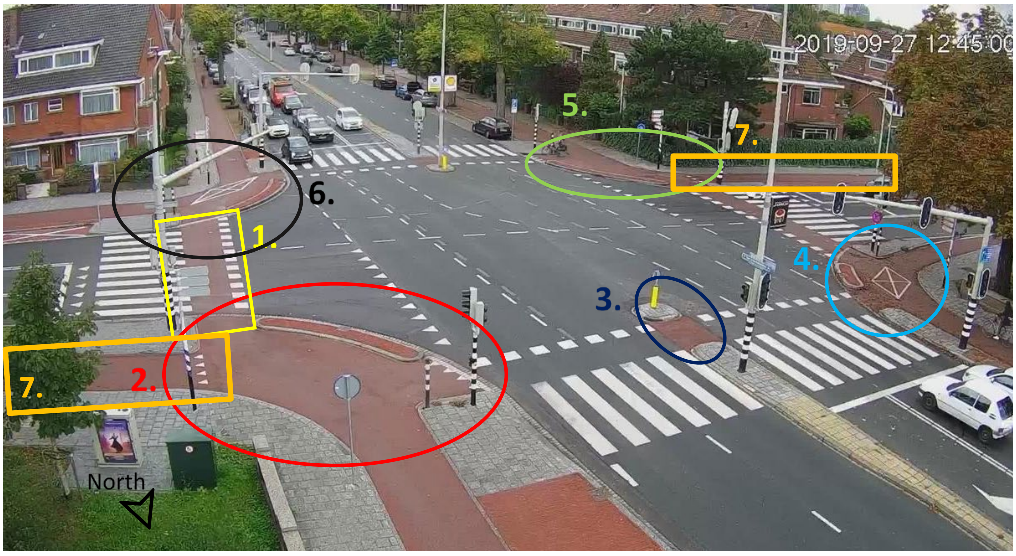


Figure 2.12 Alkemadelaan intersection after improvements



3 Data Analysis

3.1 Data Collection and Selection of Good Videos

Video data collection was done by the external company Connection Systems. The cameras were setup on a high pole with the camera adjusted at an angle capturing the intersection and approaches. Video data was collected continuously for a duration of one week (*Table 3.1*)

To perform the analysis, good quality and reliable trajectory data needs to be extracted. Processing the video data and obtaining good quality trajectories relies on the quality of the video. Night time analysis is problematic with an RGB camera as the contrast between road users especially pedestrian and cyclists and the road is quite low. In addition to that, the lack of lighting is also problematic for the detection of road users. Another element that reduces trajectory extraction quality is weather conditions. Rain and windy periods can result in rain drops on the lens and shaking of the camera. Very sunny conditions are also not ideal since the shadow cast by the road users can be detected as a road user. Other issues include the height and angle of the camera, where at a lower height, road users can be blocked by other road users. Obstacles on the road such as a traffic light pole, a tree or traffic sign can also block or cut off the trajectory of the road users.

To ensure the quality of the trajectory data is sufficient for analysis, all collected video data was manually checked, and videos with good quality were selected for further analysis.

3.2 Intersections

At the first intersection, video data from the base scenario was collected from the 22nd to 28th of November 2017, and from 5th to 11th of December 2018 in the after scenario. Both before and after videos had issues such as slight shaking of the camera due to wind, rainy periods and some raindrops on the lens, and glare due to sunny periods and reflection of vehicle lights on the wet pavement. Therefore, all night-time videos and those with the mentioned issues were removed from the analysis batch. After removing those videos, 36 hours of reasonable quality video data were selected from the before scenario and 40 hours were selected from the after scenario at the Jonckbloetplein intersection for further analysis.

At the second location, the video from the before scenario was collected from the 22nd to 28th of November 2017, and the after-scenario video data recording was from 21st of September to 2nd of October 2019. After filtering out the unsuitable videos, 40 hours of clear video data was selected from the before, and 40 hours from the after scenario.

Table 3.1. Data collection information from two intersections

	Jonckbloetplein		Alkemadelaan	
	Before	**After**	**Before**	**After**
Video data collected from	22nd to 28th November 2017	5th to 11th December 2018	22nd to 28th November 2017	21st of September to 2nd October 2019
Issues for excluding video data	wind, rain, glare			
Good quality video	36 hours daytime	40 hours daytime	40 hours daytime	40 hours daytime

3.2.1 Jonckbloetplein Scenarios

The scenarios that are analysed at the Jonckbloetplein intersection are indicated below in *Figure 3.1*, where the dark blue line indicates the car manoeuvre and the light blue indicates the interacting cyclist manoeuvre. These scenarios were selected due to the infrastructural and traffic light phase changes at the intersection as well as the camera view. Object detection is most accurate when the road users are clearly visible, which at this location is the lower left corner of the frame. Scenario 1 is selected since the highest risk of cyclist-car accidents have been shown to be between through cyclists and right turning cars (Herslund & Jørgensen, 2003; Räsänen & Summala, 1998; Summala et al., 1996; Zangenehpour et al., 2016). Scenario two is selected to check whether the change in location of the cyclist crossing affects the number of conflicts with left turning vehicles. In addition to that, scenario 3 and 4 are selected due to the introduction of a dedicated green phase for the left turning cars.

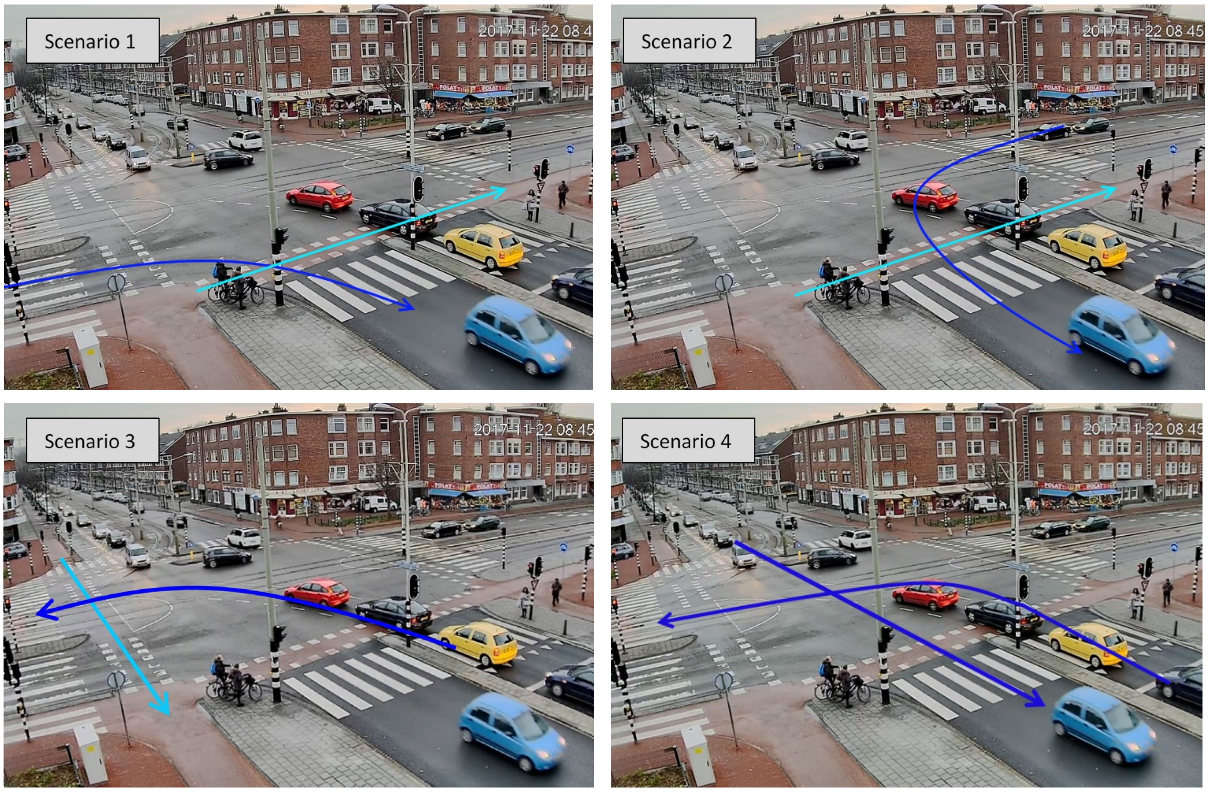


Figure 3.1 Road user interactions considered at Jonckbloetplein (car movement in dark blue, cyclist movement in light blue)

3.2.2 Alkemadelaan Scenarios

The conflict scenarios analysed at this intersection are shown in *Figure 3.2*. The car trajectories are indicated by the dark blue arrows and the conflicting cyclist movement are indicated as light blue. These scenarios are selected due to the infrastructural redesign of the intersection. Scenario 1 is selected since the left turning cyclist box is removed from the intersection and a dedicated cyclist crossing is added where the cyclists have to wait for the green phase to turn left instead of checking for a safe gap to travel left. Scenario two is selected, similar to the Jonckbloetplein location where right turning cars and through cyclists are at a higher risk, and there are several improvements done at that location (change in cyclist stop line location, implementation of a small island to separate cars, and more stopping space for cyclists). Scenario 3 is selected since in the before scenario, cyclists traveling through had to travel between right turning and through vehicles on the road, which is changed to a dedicated cycle track on the right side of the road and a dedicated cyclist crossing. The interaction with other road users is not dealt with in scenario 3, since the change in cyclist trajectories is the focus of this scenario.

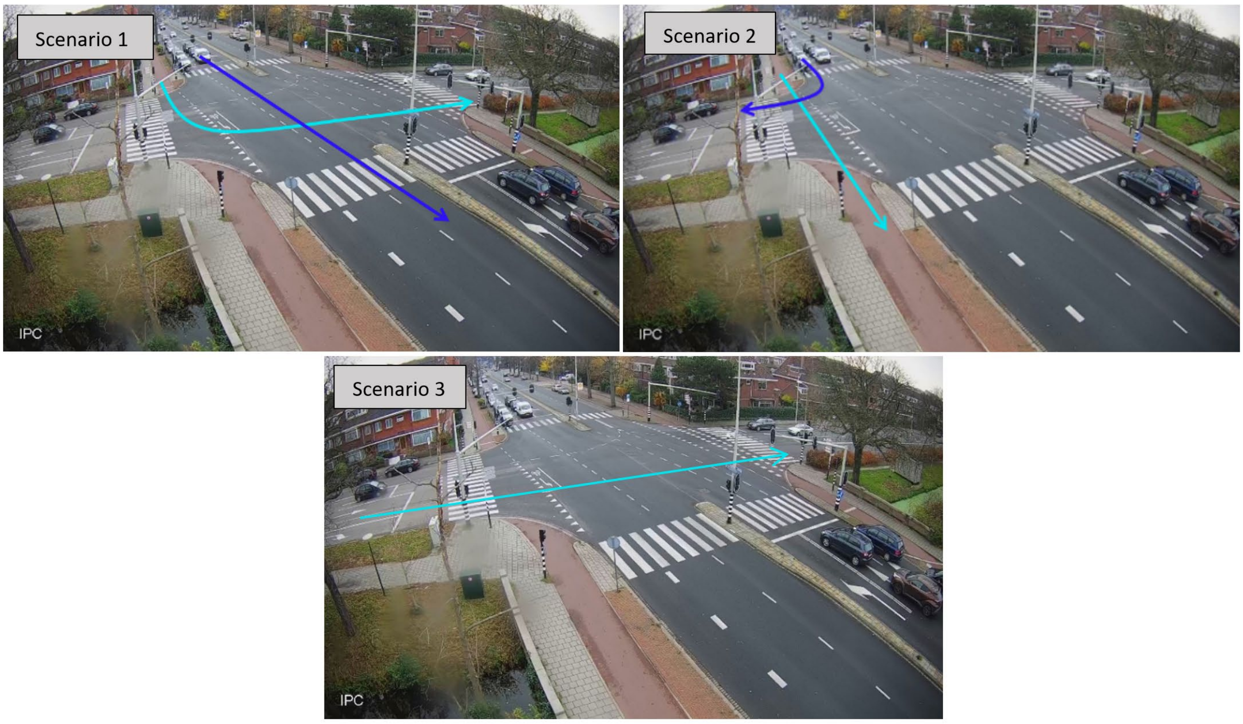


Figure 3.2 Road user interactions considered at Alkemadelaan (car movement in dark blue, cyclist movement in light blue)

4 Results

4.1 Data Analysis Method Comparison

The video data analysis performed by Brisk Synergies provided reliable results that covered most of the variables including: the location of the cyclist trajectories, road user speeds, traffic conflict points, PET safety indicators and traffic counts. Mobycon performed automated counts and safety analysis on the after scenario at the Alkemadelaan location. These results obtained from the automated analysis tools are presented in this section.

4.2 Jonckbloetplein

In *Figure 4.1*, roughly 100 cyclist trajectories are plotted to show the before (red) and after(blue) trajectory locations. The redesign of this intersection included the shifting of the bicycle crossings to further away from the intersection. The red trajectories from the before scenario are concentrated closer to the intersection. The change in cyclist trajectories is visible after the cyclist crossing was moved further away from the intersections. Therefore, the change in infrastructure indeed lead to the intended change in cyclist behaviour.

Figure 4.1. Sample of cyclist trajectories before and after infrastructural changes

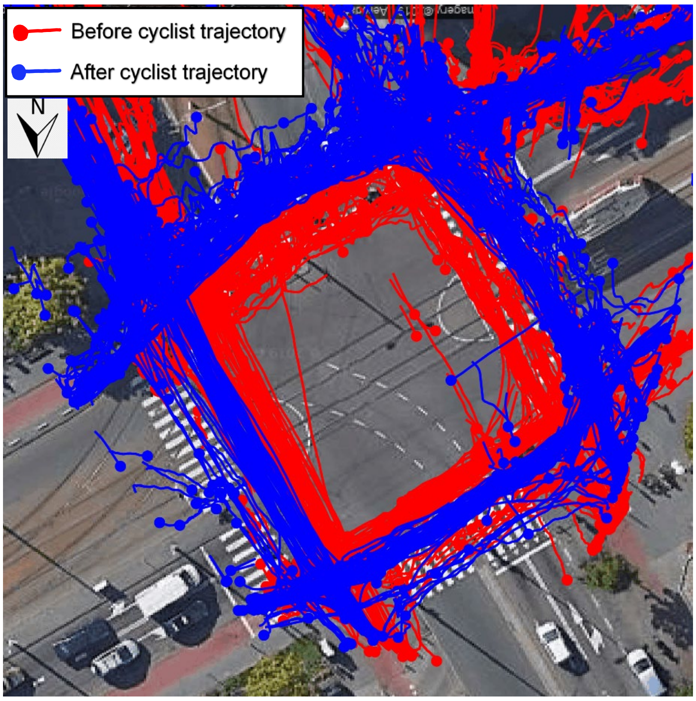
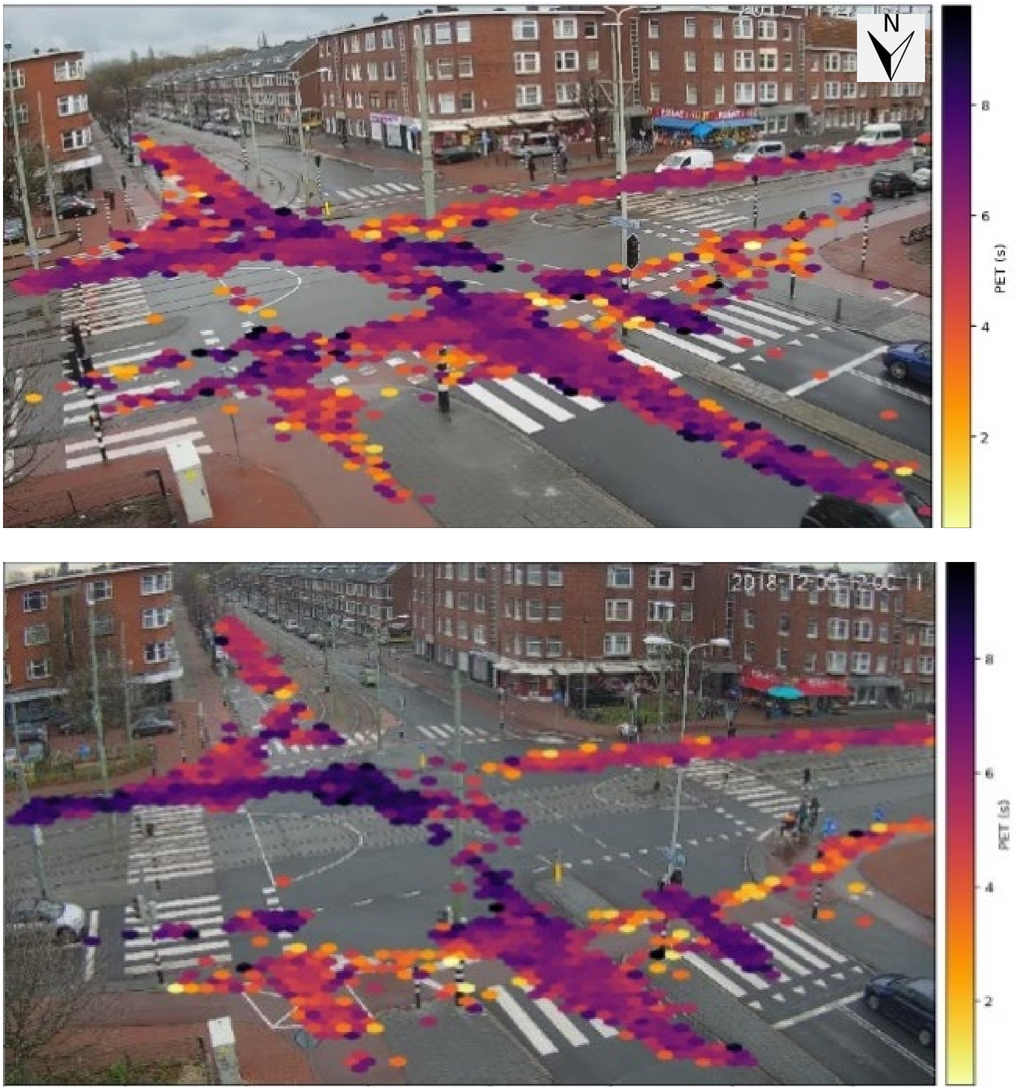


Figure 4.2 shows the collision points heatmap between all road users in the before and after scenario. Looking at the conflict heatmaps in *Figure 4.2*, most PET values are above 2s which

indicate safe interactions. In General, the before scenario collision points are scattered starting from where the intersection starts to the centre of the cyclist crossing lane. In the after redesign situation, the conflict points are more concentrated and start further away from the start of the intersection possibly due to the presence of the island and the wider right turns performed by cars. These figures are useful for identifying potential danger zones at an intersection.

Figure 4.2. Conflict heatmap from before and after infrastructural changes at Jonckbloetplein



4.2.1 Movement 1: Through Cyclists & Right Turning Cars

In this section, the interaction between through cyclists and right turning cars at the North corner of the intersection is evaluated. *Figure 4.3* shows the average trajectory manoeuvres for the through cyclists and right turning cars, with their start stop/start location indicated with circles.

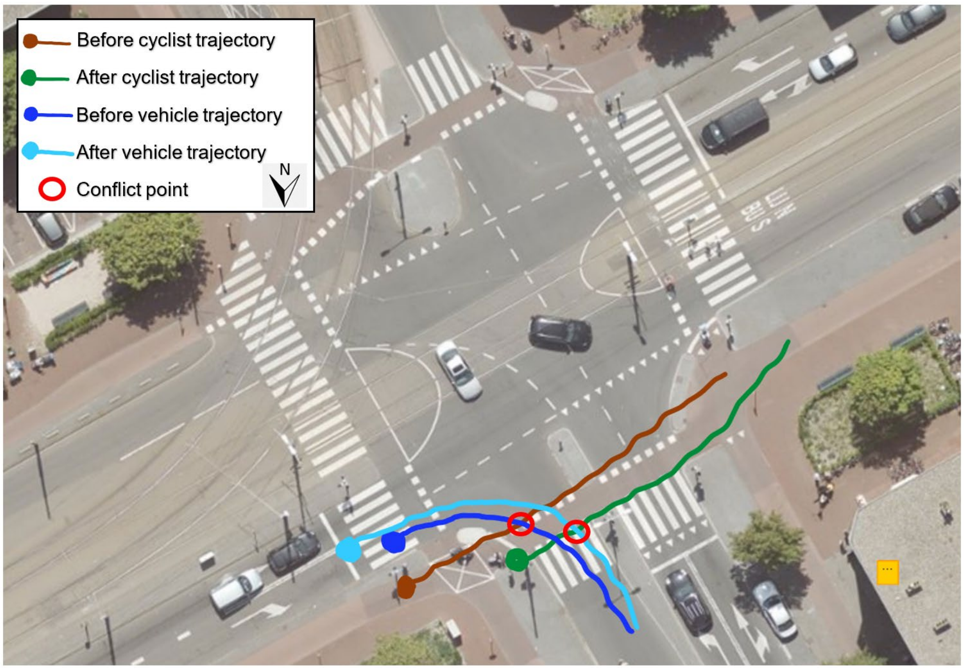


Figure 4.3. Before and after manoeuvres of cyclists crossing straight through the intersection from the cycle path along the Governor's Avenue, and right turning motor vehicles – simultaneous green traffic light

For cyclists in the after scenario, in addition to traveling further away from the intersection, their stop/start point is closer to the road compared to the before scenario, where the cyclist stop line was further away from the road. As mentioned in *Section 2.4*, the reason for moving the stop line closer to the road was to make stopped cyclists more visible to turning cars. Moreover, the before-scenario cyclists were provided more space to gain speed before arriving at the road which lead to higher cyclist speeds interacting with right turning vehicles.

Right turning car trajectories in the before scenario performed a slightly sharper turn, compared to a wider turn in the after scenario, which could be due to the small island separating the space between cyclists and the right turning cars.

The wider and longer arc that motor vehicles make before they cross with the cyclists indicates that motor vehicles and cyclists can better detect and anticipate each other to avoid critical situations (conflicts). The potential collision point has now changed from an acute velocity angle between cars and cyclists to a more perpendicular angle allowing for cars to detect the cyclists from the front and not a side view.

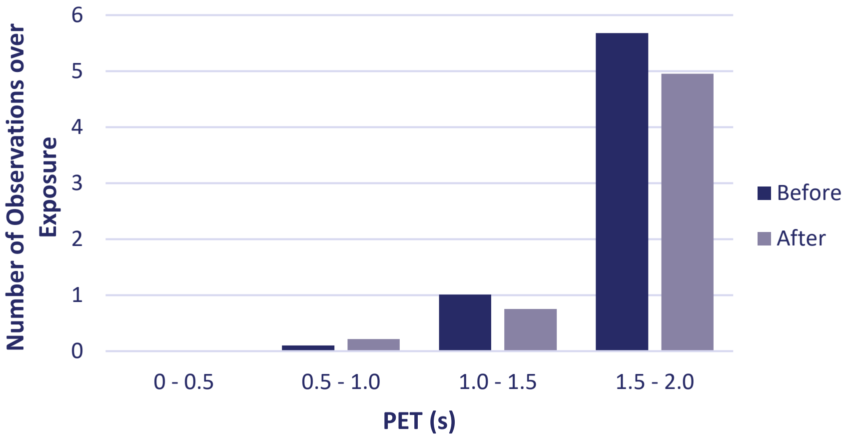
Table 4.1. Movement 1: Traffic volume and risk (conflict frequency) for before and after intersection redesign

Time	Vehicle volume	Cyclist volume	PET (s) category and frequency (risk)				
			0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	Total
Before	6,245	4,598	0.0 (0)	0.1 (3)	1.0 (29)	5.7 (163)	6.8 (195)
After	3,647	2,546	0.0 (0)	0.2 (2)	0.8 (7)	5.0 (46)	5.9 (55)
% Change	-42%	-45%	-	+106%	-25%	-13%	**-13%**

The total number of conflicts (PET) has decreased from 195 to 55 conflicts, considering the change in traffic volume presented in *Table 4.1*. However, the number of relatively serious conflicts (PET= 0.5-1.0) shows no change.

Looking at the different PET categories with respect to traffic flow, *Figure 4.4*, indicates a slight decrease in lower severity conflicts. The slight increase in the relatively high severity conflict (between 0.5 and 1.0 seconds), is based on a change from 3 to 2 conflicts which is not enough to draw a conclusion.

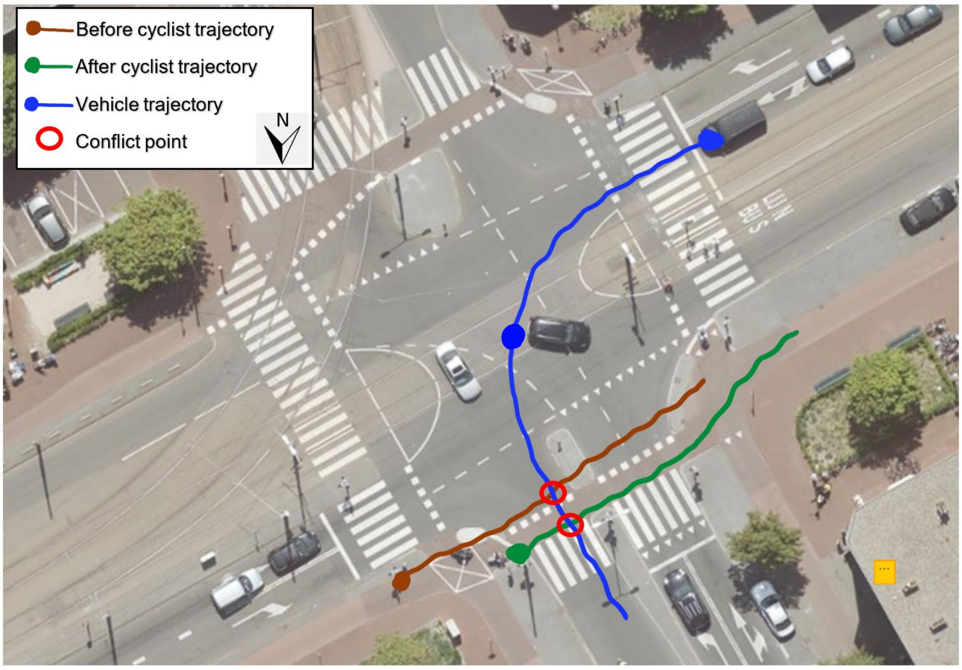
Figure 4.4. Movement 1: Number of conflict observations over the product of vehicle and cyclist flow from before and after the redesign



4.2.2 Movement 2: Through Cyclist & Left Turning Car

Scenario 2 highlights the interaction between through cyclists and left turning cars along the North approach. The average trajectories are shown in *Figure 4.5* with their start stop/start location indicated with circles. There is no change in the left turning vehicle trajectory in the before and after scenario since there is no infrastructural change targeting this movement. The through cyclist behaviour is discussed in Scenario 1. The cyclists and the left-turning vehicles have a green light at the same time both before and after the redesign.

Figure 4.5. Before and after manoeuvres of cyclists crossing straight through the intersection from the cycle path along the Governor's Avenue, and left turning motor vehicles – simultaneous green traffic light



The data in *Table 4.2* show that in the post-redesign situation, the number of registered cyclists is about 45% lower than in the situation before; the number of motor vehicles is also lower by 47% in the after situation. The total number of conflicts (PET) has decreased from 38 to 8 conflicts which is a 79% decrease.

Table 4.2. Movement 2: Traffic volume and risk (conflict frequency) for before and after intersection redesign

Time	Vehicle volume	Cyclist volume	PET (s) category and frequency (risk)				
			0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	Total
Before	2,967	4,598	0.0 (0)	0.0 (0)	0.7 (9)	2.1 (29)	2.8 (38)
After	1,583	2,546	0.0 (0)	0.0 (0)	0.7 (3)	1.2 (5)	2.0 (8)
% Change	-47%	-45%	-	-	0%	-42%	**-31%**

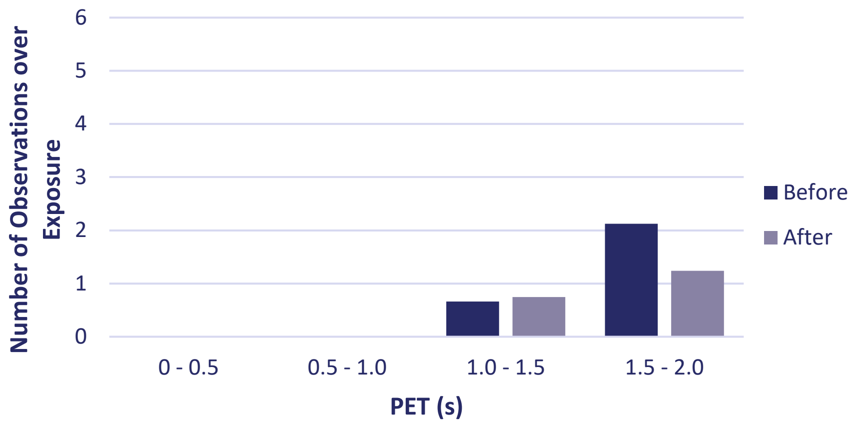


Figure 4.6. Movement 2: Number of conflict observations over the product of vehicle and cyclist flow from before and after the redesign

4.2.3 Movement 3: Through Cyclist and Left Turning Car

In this Scenario interactions between through cyclists and left turning cars are compared. The average trajectories are shown in *Figure 4.7* with their start stop/start location indicated with circles. The major redesign associated with this interaction is the change in traffic light. In the before scenario, through cyclists and left turning cars shared the same green phase, whereas in the after scenario, a dedicated green is provided for the left turning cars. There is no change in the left turning vehicle trajectory movement in the before and after scenario since no major infrastructural changes were implemented to target this movement. The through cyclist trajectories slightly move further away from the intersection due to the change in cycling crossing location in the after redesign situation.

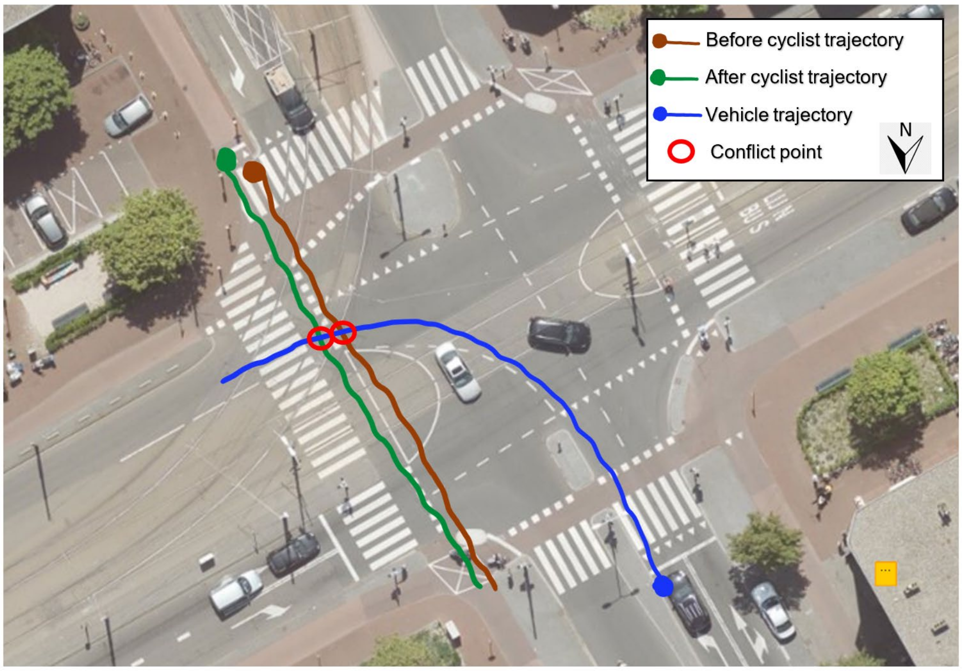


Figure 4.7. Before and after manoeuvres of cyclists crossing straight through the intersection from the cycle path along and left turning motor vehicles – shared green traffic light in before, and dedicated left turn light in after scenario

Table 4.3 summarizes the traffic flow and number of conflicts per category. A lower traffic flow is also observed in this scenario where the cyclist and car volumes were reduced 34% and 42% respectively. The reduction in number of conflicts is however more significant with a change from 122 conflicts to 8 showing a 93% improvement in safety.

Table 4.3 Movement 3: Traffic volume and risk (conflict frequency) for before and after intersection redesign

Time	Vehicle volume	Cyclist volume	PET (s) category and frequency (risk)				
			0 - 0.5	**0.5 - 1.0**	**1.0 - 1.5**	**1.5 - 2.0**	**Total**
Before	7,214	4,338	0.0 (0)	0.1 (2)	1.2 (36)	2.7 (84)	3.8 (122)
After	4,151	2,845	0.0 (0)	0.0 (0)	0.2 (2)	0.5 (6)	0.7 (8)
% Change	-42%	-34%	-	-100%	-85%	-81%	**-82%**

The high level of safety improvement can be associated with the dedicated left turn for motor vehicles. *Figure 4.8* shows the proportion of reduced conflicts normalized by exposure.

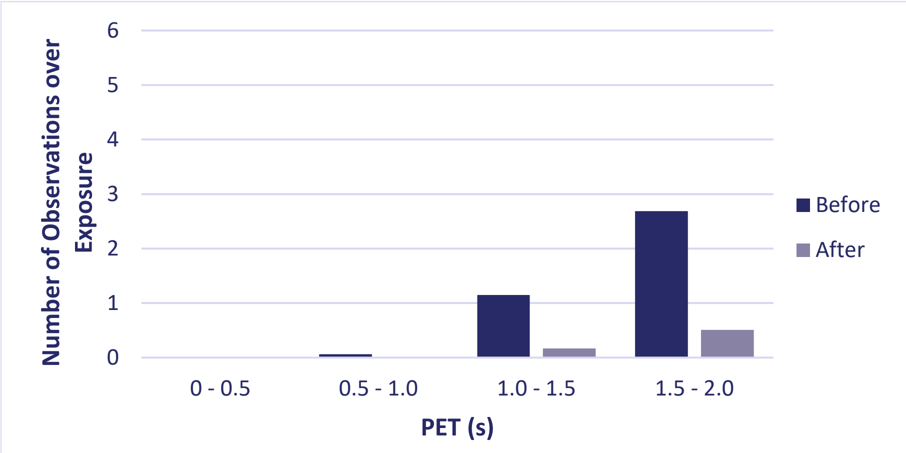
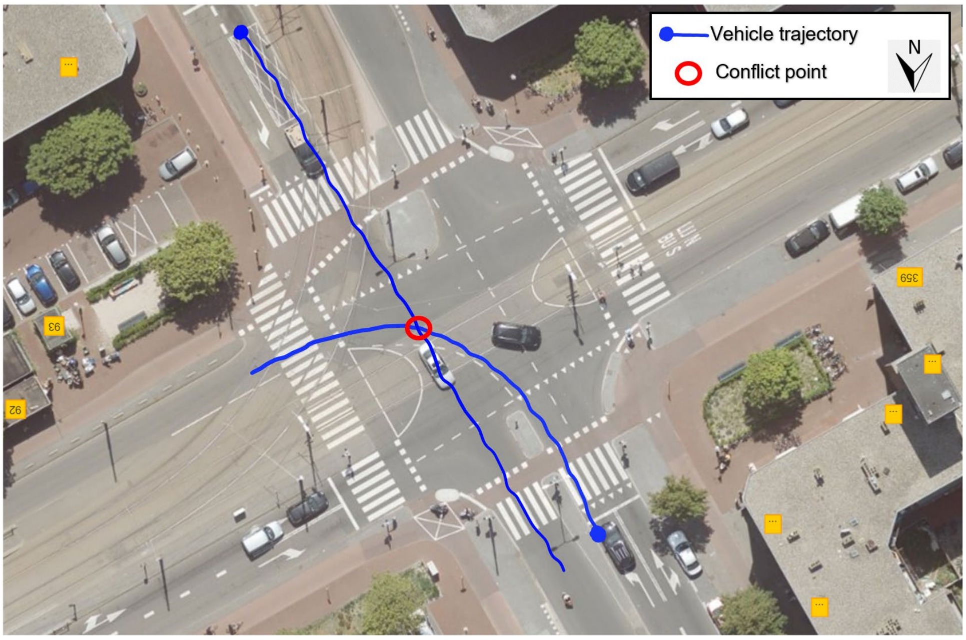


Figure 4.8. Movement 3: Number of conflict observations over the product of vehicle and cyclist flow from before and after the redesign

4.2.4 Movement 4: Through Cars & Left Turning Cars

Given the change in traffic light phase, the biggest safety improvement is expected to be observed at in this scenario, since there is a dedicated left turn light implemented in the after scenario. Through traveling and left turning cars along and left turning cars are compared, with their average trajectories shown in *Figure 4.9*. Since no major infrastructural change was implemented, the before and after trajectories did not change. However, as seen in *Table 4.4*, safety was improved significantly.

Figure 4.9. Before and after manoeuvres of through and left turning vehicles – shared green traffic light in before, and dedicated left turn light in after scenario

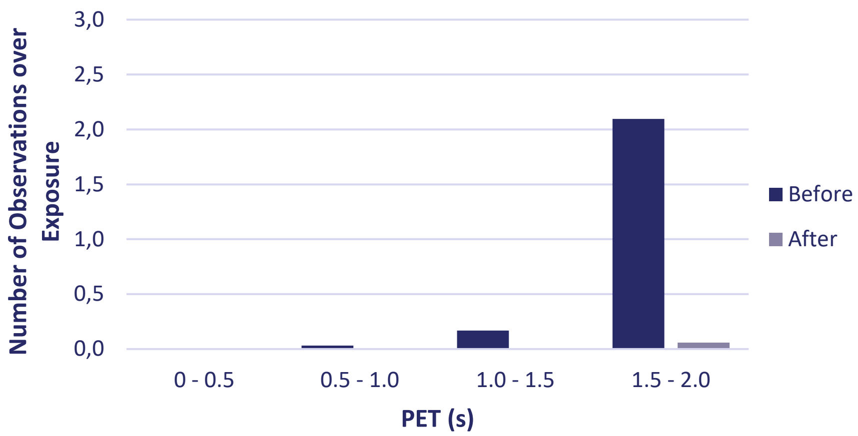


Results in *Table 4.4* and *Figure 4.10* show an 98% improvement in safety. This indicates that providing a dedicated green phase for left turns can significantly improve safety.

Table 4.4. Movement 4: Traffic volume and risk (conflict frequency) for before and after intersection redesign

Time	Turning vehicle volume	Through vehicle volume	PET (s) category and frequency (risk)				
			0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	Total
Before	7,214	14,814	0.0 (0)	0.01 (1)	0.2 (18)	2.1 (224)	2.3 (243)
After	4,151	9,009	0.0 (0)	0.0 (0)	0.0 (0)	0.1 (2)	0.1 (2)
% Change	-42%	-39%	-	-100%	-100%	-97%	**-98%**

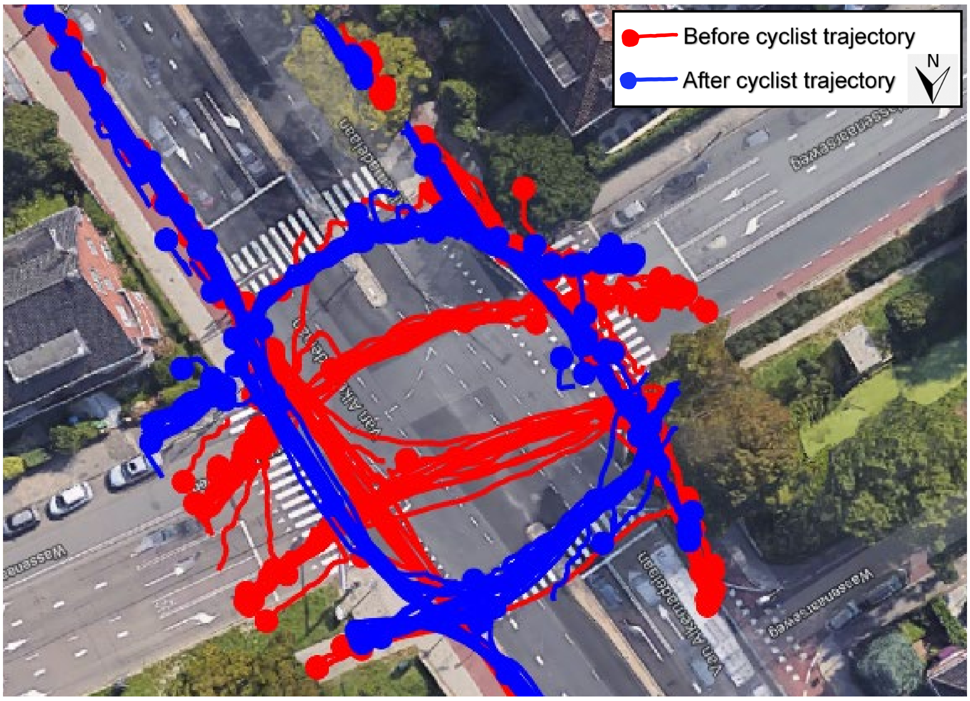
Figure 4.10. Movement 4: Number of conflict observations over the product of turning and through vehicle flows from before and after the redesign



4.3 Alkemadelaan

Figure 4.11 shows a plot of 50 trajectories from before and after the redesign of the intersection. The main change is visible where The left turning box is removed from the centre of the intersection and left turning cyclists from North can use the dedicated cycling space to turn left at the crossing. In addition to that, the cycle paths located between the through-vehicle and left-turning vehicle lanes are changed to a dedicated cycling space along the right side of the road. Cyclist manoeuvres in the after scenario are more predictable and concentrated to the crossing area compare to the before scenario where unusual manoeuvres are observed especially for cyclists going through the crossing and turning left.

Figure 4.11. Sample of cyclist trajectories before and after infrastructural changes



The conflict heatmap provided in *Figure 4.12*, plots the density of all conflicts occurring at this location (includes vehicle-vehicle conflicts as well). Generally looking at the image indicates a lower frequency of conflicts, and a shift in conflicts along the south east corner of the intersection where the cycle path was moved further away from the intersection. In the same location, the darker colours indicate an improvement in safety with higher PET values.

Figure 4.12. Conflict heatmap from before and after infrastructural changes at the Alkemadelaan intersection

4.3.1 Movement 1: Left Turning Cyclist and Through Car

In *Figure 4.13*, the manoeuvre is indicated in which cyclists cross the intersection to the Wassenaarseweg from the bike path along the Van Alkemadelaan on the left. The blue arrow indicates the flow of traffic on the roadway, which follows the Van Alkemadelaan with the same green light in the same direction as the cyclists. The other two arrows (brown and green) respectively indicate the crossing of the cyclists before and after the redesign. Before the redesign, the cyclists had to stop halfway through the intersection, and wait for a safe gap to travel to the other side of the intersection to complete their left turn. After the redesign, the cyclists first cross the Wassenaarseweg and then have to wait for another green light, to cross the Van Alkemadelaan.

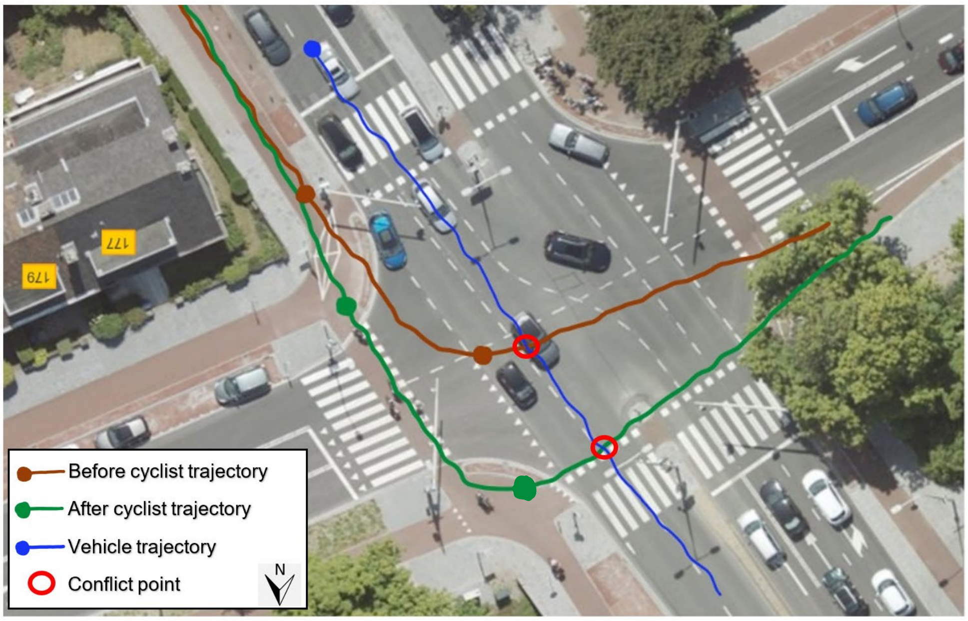


Figure 4.13. Before and after manoeuvres of cyclists turning left and through turning motor vehicles – bike box in middle of intersection in before scenario is replaced with dedicated cycle path and cycle crossing on all approaches

The safety improvement of removing the bicycle stop box, and providing dedicated cycle path and crossing along all approaches is 92% (*Table 4.5*). It is clear that in the before scenario, cyclists were stopping in the centre of the intersection which results in many unsafe interactions with motor vehicles. This is eliminated when the cyclists make a left turn using the dedicated space to stop at the intersection corner, wait for the green light and cross through the dedicated crossing away from motor vehicles.

Table 4.5. Movement 1: Traffic volume and risk (conflict frequency) for before and after intersection redesign

Time	Vehicle volume	Cyclist volume	PET (s) category and frequency (risk)				
			0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	Total
Before	19,462	1,826	0.0 (0)	0.03 (1)	0.6 (22)	3.5 (124)	4.1 (147)
After	18,248	2,705	0.0 (0)	0.02 (1)	0.02 (1)	0.3 (15)	0.3 (17)
% Change	-6%	+48%	-	-28%	-97%	-91%	**-92%**

The before after results are summarised in *Figure 4.14*, where the y-axis shows the normalized number of conflict observation by the product of the cyclist and vehicle traffic flows.

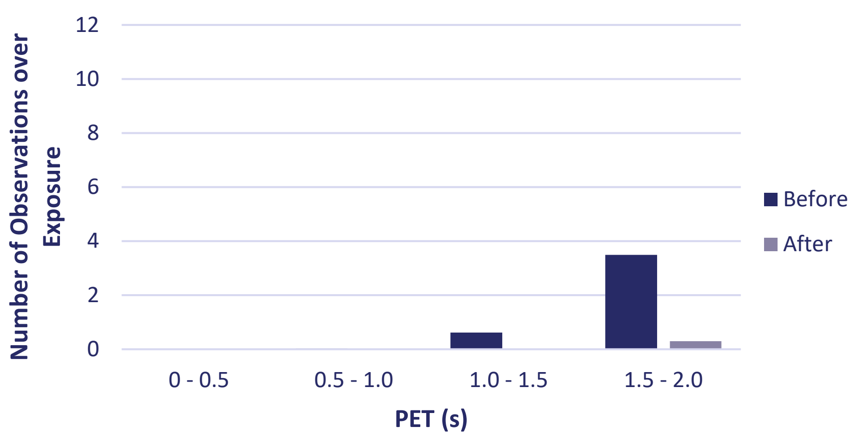
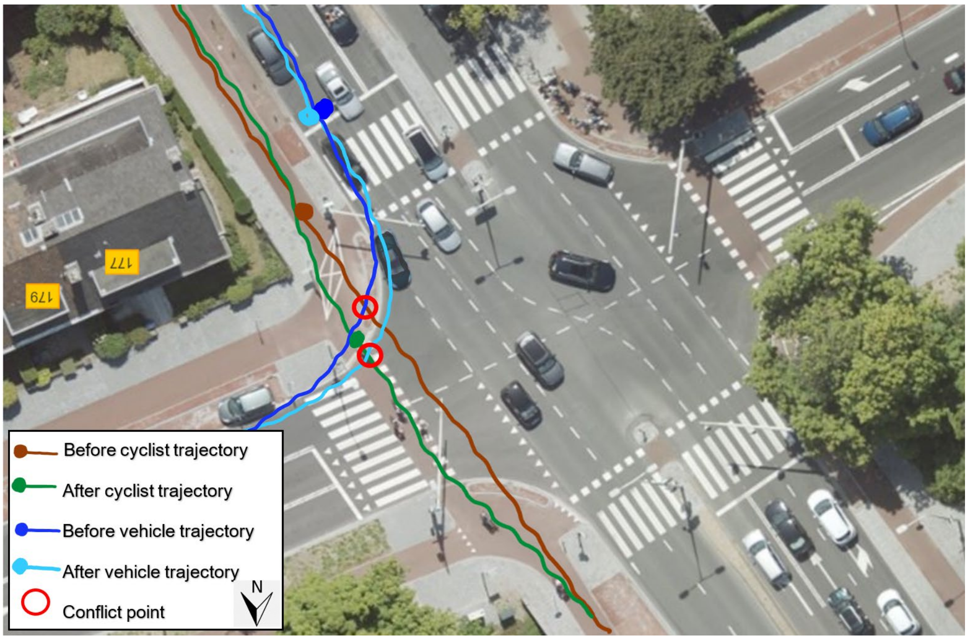


Figure 4.14. Movement 1: Number of conflict observations over the product of vehicle and cyclist flow from before and after the redesign

4.3.2 Movement 2: Through Cyclists and Right Turning Cars

Figure 4.15 shows the interaction between through cyclists and right turning cars in the before and after redesign. It is visible that the average cyclist in the after scenario (in green) is moved slightly further into the road given the shift of bike crossing. The vehicles perform a wider right turn after the implementation of the cycling island restricting the vehicles to make a sharp turn as they did in the before scenario (dark blue). Both movements have a simultaneous green, therefore a high number of interactions are expected. Similar to movement 1 at Jonckbloetplein, the conflict point shifts further away allowing for a perpendicular view instead of a side view of the cyclists from the drivers perspective.

Figure 4.15. Before and after manoeuvres of through-traveling cyclists and right turning motor vehicles – simultaneous green for both movements in both scenarios



The data in *Table 4.6* shows that in the post-redesign situation, the total number of conflicts (PET) has decreased from 90 to 74. A total improvement of 33% is observed in risk.

Table 4.6. Movement 2: Traffic volume and risk (conflict frequency) for before and after intersection redesign

Time	Vehicle volume	Cyclist volume	PET (s) category and frequency (risk)				
			0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	Total
Before	3,716	2,054	0.0 (0)	0.4 (3)	1.8 (14)	9.6 (73)	11.4 (90)
After	3,503	2,769	0.0 (0)	0.0 (0)	1.4 (14)	6.2 (60)	7.6 (74)
% Change	-6%	+35%	-	-100%	-21%	-35%	**-33%**

Figure 4.16 indicates a 100% reduction in severe interactions of 0.5 to 1.0 seconds, and a further 21% and 35% reduction in the medium risk and low risk categories.

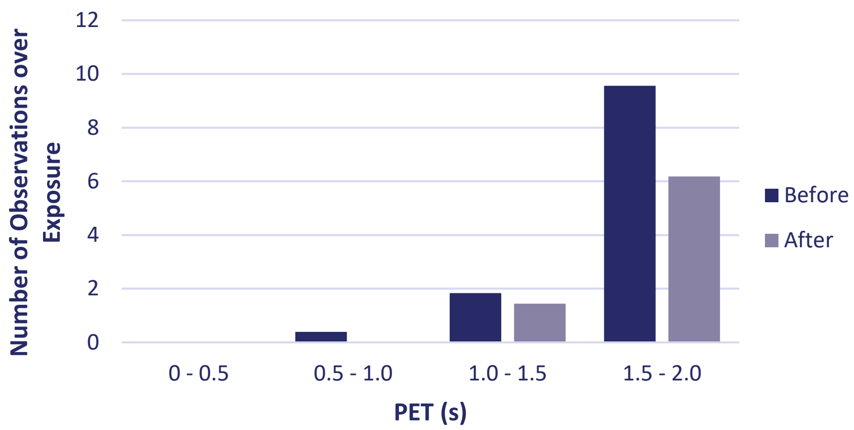


Figure 4.16. Movement 2: Number of conflict observations over the product of vehicle and cyclist flow from before and after the redesign

4.3.3 Movement 3: Through Cyclists

Figure 4.17 shows three different through manoeuvres in before scenario: two from the in-between bike lane, and one from the sidewalk which is prohibited.

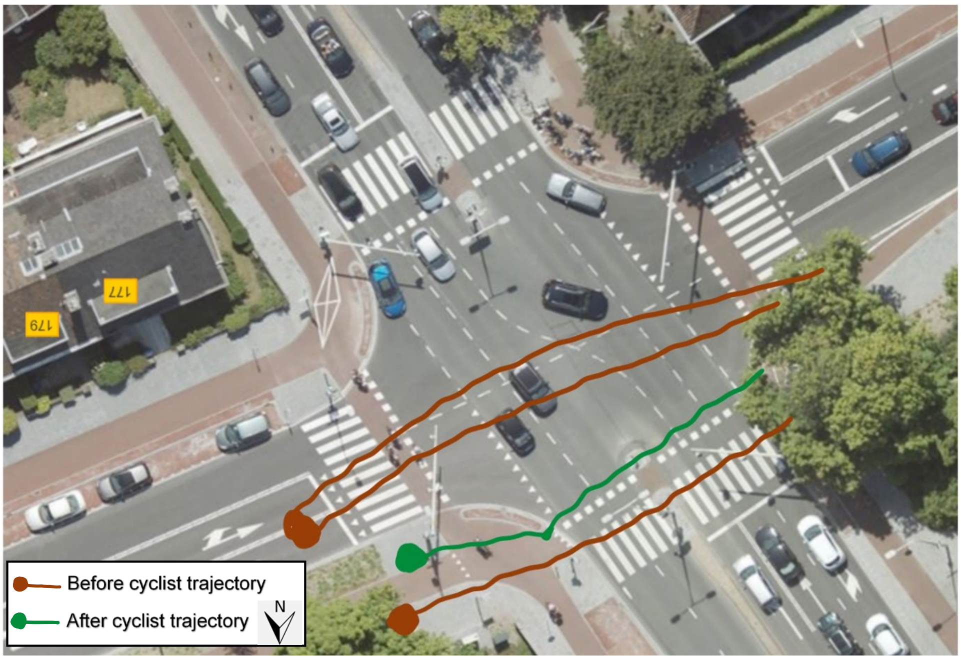


Figure 4.17. Average cyclist movement from before and after redesign

This is due to the change in cycle path location. In the before scenario, cyclists had to travel between the through and right turn vehicle lanes to cross the intersection. In that case, some cyclists performed three distinct manoeuvres one slightly to the right and the other slightly to the left through the intersection, and the last one being through the side walk and pedestrian crossing. The three different cyclist movements traveling in the same direction was reduced to one movement in the after scenario, since cyclists were given dedicated space to travel and cross the intersection.

5 Discussion of Results

In general, the highest risk is observed at Alkemadelaan with the right turning car and through cyclists, the second highest risk is with the same interaction at Jonckbloetplein, which also shows the lowest improvement in safety. The risk is calculated by the ratio of conflict frequency and cyclist and vehicle volume in that direction.

Table 5.1. Comparison of results stratified by interaction movement

Movement	Location	Before risk	After risk	% Risk improvement
Right turn car Through cyclist	Jonckbloetplein	6.8	5.9	13 %
	Alkemadelaan	**11.4**	**7.6**	33 %
Left turn car Through cyclist or Through car	Jonckbloetplein	2.8	2.0	31 %
	Jonckbloetplein	3.8	0.7	82 %
	Jonckbloetplein	2.3	0.1	98 %
Through car Left turn cyclist	Alkemadelaan	4.1	0.3	**92 %**

*Table 5.1*indicates that the dedicated left turn phase had the highest improvement in safety, however, the initial risk was not remarkably high (2.8 and 3.8 compared to right turn car risks of 6.8 and 11.4). In general, providing a dedicated green yielded a high improvement in safety.

In summary, the infrastructure changes have led cyclists to move across the intersection in the intended way. After adjustment at the Van Alkemadelaan-Wassenaarseweg, cyclists no longer travel through the middle of the intersection. The crossing pattern of cyclists is less complex and they no longer pass over the middle of the intersection plane where motorized traffic from all directions passes. This can contribute to a higher level of road safety (Gerstenberger, 2015; Herslund & Jørgensen, 2003; Nabavi Niaki et al., 2019), where a number of studies have shown that reduced complexity in traffic movements leads to increasing road safety, especially when it comes to the interaction between cyclists and motorised traffic at intersections.

The highest level of safety improvement of 92 % is achieved by removing the left turn bicycle box and providing dedicated crossing and waiting space for cyclists to travel when they have a green light.

A high reduction in risk is observed at situations where simultaneously green cyclists and motor vehicles have been replaced by dedicated green phases. Previous research (Welleman, 1982) has shown that the risk of accidents between straight-moving cyclists and right-turning motor vehicles is higher with a simultaneous green.

The shift in cyclist crossing further from the intersection plane have shown a reduction in the number of conflicts between motor vehicles and cyclists. However, this reduction is less significant than was achieved with the adjustment of the traffic light scheme. It should also be indicated that, in the current adjustments, the bicycle crossings are shifted to a limited extent (approx. 2-3 metres). As a result, the view of the bicycle crossing by the drivers of the motor vehicles - due to the longer turn and thereby increasing the angle of view - has been improved to a limited extent.

We did not include all possible manoeuvres and conflicts in our analyses. Those that were selected are considered to represent the effects of what can be expected from comparable other locations that were not analysed in this study.

The method of analysis used – the automatic analysis of video recordings of traffic flows at intersections – has shown that it can give indications of changes in the degree of road safety. A number of points are important to mention:

- The method of analysis used (Brisk) is an example. There are several methods of analysis developed for the automatic mapping of traffic flows and the generation of road safety indicators such as traffic conflicts
- The analysis method makes it possible to analyse long-lasting video observations without high costs from individuals who need to visually assess images
- In addition to evaluating interventions, it is also possible to identify relatively dangerous locations and analyse the traffic process with a view to taking measures
- Analysis of video images is not (yet) possible under low light conditions using RGB cameras

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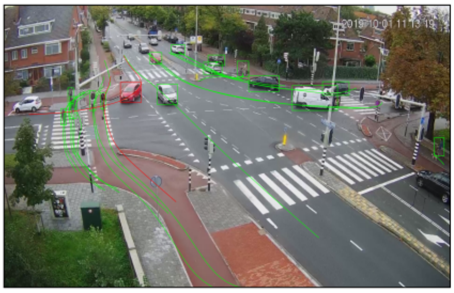
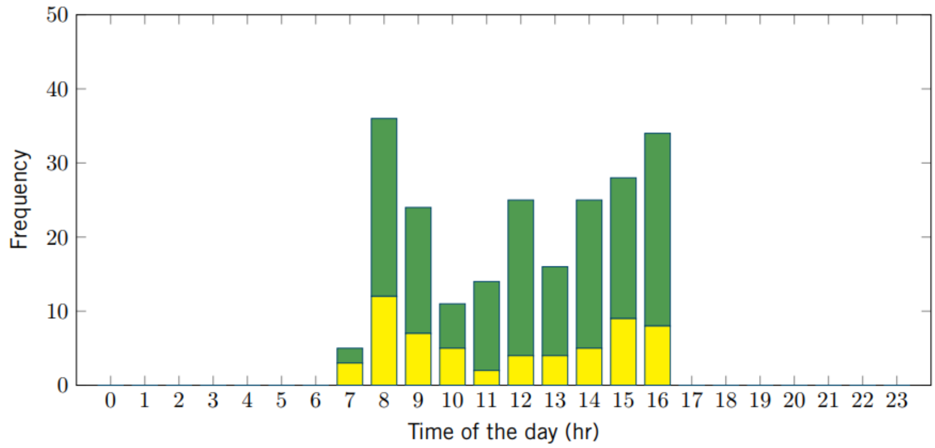
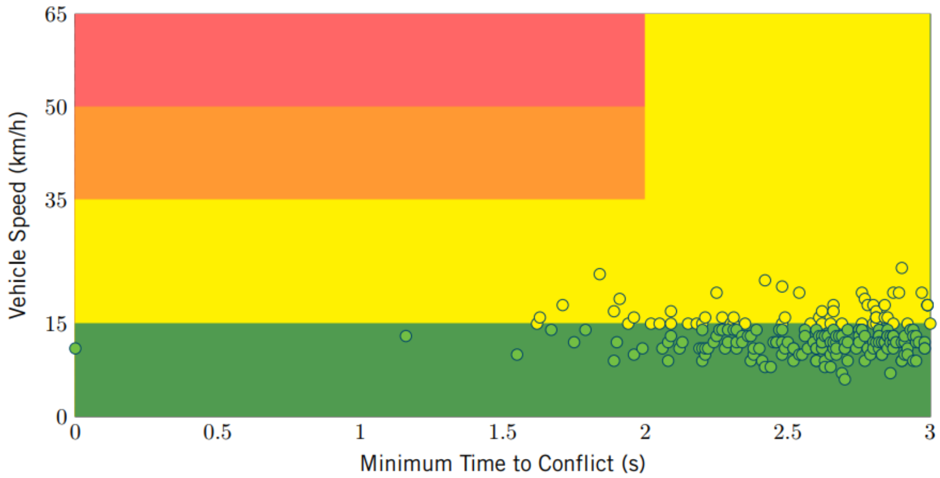
Appendix A MicroTraffic Safety Analysis by Mobycon

The following figure shows a sample of the MicroTraffic safety results which indicates the risk based on conflict frequency and speed. However, since they were contacted closer to the end of the project, time and budget limits did not allow for a full comparison analysis of the intersections by MicroTraffic.



Risk Level	Critical Risk	High Risk	Medium Risk	Low Risk
Measured Frequency	0	0	59	159
Annual Estimate	0	0	6712	18089
Conflict Rate (%)	0	0	1.73	4.65
Relative Risk	NA	NA	NA	NA





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