BSc Civil Engineering Thesis

Department of Engineering Technology

Redesigning an Intersection to Accommodate Municipal Area Development Plans

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Preface

The writing of this thesis project is a part of the final semester of the BSc Program Civil Engineering at the University of Twente in Enschede, the Netherlands. The thesis is conducted as an external graduation project in conjunction with the Fachhochschule Münster in Münster, Germany.

In communication with the municipality of Münster, an intersection is selected for a redesign in the direct vicinity of the university campus. The redesigning of the intersection is viewed as an element of an overall transition of the surrounding area from a car-centered philosophy to the recent objectives of the municipality rooted in sustainability.

A large thank you goes out to Professor Dr. -Ing. Hartz, my external supervisor at the FH Münster, as well as Professor Dr. Ir. van Berkum, my internal supervisor at the University of Twente. Both supervisors dedicated considerable time to my efforts with weekly meetings and valuable inputs to continue improving my analysis and working process. Despite organizational challenges, both professors showed valuable flexibility and adaptability, ensuring I could successfully complete this project.

An additional thank you goes out to A. Pott, responsible for traffic control and management in the municipality of Münster. From initial suggestions and information about the intersection in question to being available for questions and providing opinions and feedback, he functioned as a valuable contact and representative of the municipality’s perspectives.

Executive Summary

The intersection between the *Correnssstraße* and the *Henriette-Son Straße/Mendelstraße* in the west of the German city Münster is currently inadequately designed for its traffic flows. Originally designed in the 1960s in complement to the construction of vast university educational facilities, the intersection is focused on maximizing motorized access to the university buildings. Since its initial construction, however, the municipality's priorities in mobility infrastructure have shifted drastically towards the three pillars of sustainability and new developments to surrounding areas, as well as the *Correnssstraße* itself, warrant a fundamental redesign of the intersection.

From a preselection of four alternative designs, a single design alternative is chosen as the most optimal according to a set of design criteria and weightings decided according to the municipality's goals and values, as well as considering the interests and influence of certain stakeholders. The different alternatives are modeled as microsimulations and evaluated in respect to the performance of the current situation, providing insight into the benefits and drawbacks of each design. In doing so, the addition of criteria other than those used for this investigation is possible to make an administrative decision on which intersection should be constructed.

According to the investigation, a segregated roundabout services the traffic flows and wishes of the municipality and stakeholders best. It performs particularly well in its environmental and sustainable travel options, whilst producing minimal to no additional queues or travel time increases. Of the chosen alternatives, it also performs second only to a signalized crossing in safety. In the final design recommendations, certain additions to the final design are suggested to mitigate the negative safety effects without influencing the positive performances of the roundabout.

Taking a broader perspective, the results obtained in this work can be generalized and extracted to be applied to other intersections in Münster, as well as elsewhere. By investigating the performances of the different alternatives separately, the intermediate results generate insight about the performance of certain design elements on the safety, environmental, sustainable mobility, and accessibility ratings. Thereby, given differing priorities or different traffic demands per intersection, another solution may be more viable. Despite these drastic changes in values, the same methodology may be applied to obtain representative results, albeit with different criteria weightings.

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1. Introduction

Münster gestaltet die Mobilität der Zukunft.

“Münster shapes the mobility of the future.” Under this slogan, the German city of Münster aims to pursue the three pillars of environmental, social, and economic sustainability. In doing so, a set of goals for all mobility infrastructure is set, including the reduction of car traffic and its sound and air pollution, an increase in traffic safety, and a significant prioritization of sustainable modes of travel such as the bicycle and public transit [1]. At the same time, urban areas surrounding the center of Münster are currently in the design phase of restructuring. The aim is for these quarters to become inspirations for other urban developments, granting the name “*Modellquartiere*” [2]. One of these quarters is centered around the various educational facilities of the universities in Münster, which were originally designed in the 1960s to accommodate a car-centered commuting of students and professors alike [3]. Several of the roads in the campus area are therefore requiring a redesign to reflect the priorities of the municipality, with particular attention to be paid to the major intersection nodes. In this paper, an examination of one of these nodes is conducted by establishing design criteria, based on which a recommendation is produced for the municipality using microsimulations.

2. Research: Problem Analysis

2.1 Design Specifications

2.1.1 Design Goal & Scope

The research aim corresponds to the overall goal of the design project. Consequently, the principal aim is formulated as follows:

> *The research aim is to redesign the intersection between the Corrensstraße and Mendelstraße in Münster to accommodate the projected traffic flows and "Knowledge-Quarter" plans of the municipality via the use of microsimulation software.*

Although similar conditions certainly apply to a wide range of intersections, finding a generalized solution would result in several policy suggestions rather than a design. Instead, the junction in question is considered a case study and worked through in detail considering various scenarios to generate a solution set that is feasible and fulfils the specified research aim above. These solutions can then potentially be considered generalizable as viable solutions for traffic nodes facing similar conditions.

The municipality of Münster strictly defines the boundaries of the research project to the traffic node in question, and not adaptations to the surrounding road geometries. Consequently, the research scope is spatially well-defined. Additionally, the context of development surrounding the intersection is given by municipal plans which depict two different developments and a consequent traffic demand scenario. A significant degree of freedom is kept in the formation of design alternatives for the intersection, with fundamental geometric changes entirely possible, including the removal of signalization. In this regard, therefore, the research scope is bounded by national German legislature and regional policies.

2.1.2 Research Questions

Given the concrete aim and scope of the research, a framework is presented below in Figure 2.1. In this framework, the research aim is listed on the far right of the schematic. The necessary research objects are presented in the center column, along with the current situation and external conditions influencing the alternatives created. On the left side of the figure, the processes leading to the creation of alternatives are shown, with three different information sources. These are literature on the nearby development plans, literature on intersection design including legal guidelines, and the problem analysis conducted below.

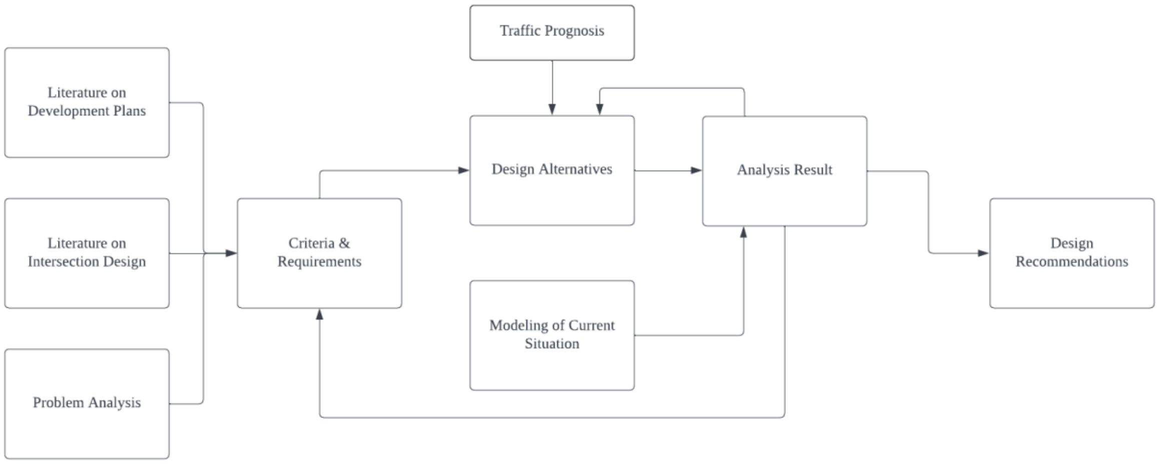

Figure 2.1: Research framework. Created using Lucidchart.

Along with the research framework, guiding research questions are necessary to accompany the process associated with reaching the final design recommendations outcome. The methodology to answer these questions is shown in Figure 2.2.

First, various literary sources are used to establish decisive values relevant to creating design criteria. The values not only shape the different criteria to be used to evaluate distinctive designs, but also define the weightings to be applied to indicate the importance of each criterion. Therefore, the following questions are posed for this section of the study:

Q1: Which values are relevant to the design of the intersection?

> *Q1.1: What values are expressed in the Münster Modell Quartier plans for the area?*
>
> *Q1.2 Who has an interest in modifying or retaining the current situation?*
>
> *Q1.3 Which values are expressed by the aforementioned stakeholders?*
>
> *Q1.4 How can the relative importance of stakeholders and their associated values be quantified?*

Second, the problems with the intersection must be formally identified and categorized. The identification of problems can occur on a purely objective basis by considering the safety of users in various situations and the objective facts of the intersection, but also through the lenses of the various stakeholders identified in the previous question. In doing so, the potential inventory of problems is expanded, and more insight can be gained. As an addition, the two sub-questions categorize the problems of the intersection to determine which evolve into design requirements and which influence the design criteria.

Q2: What are the problems with the current state of the intersection?

Q2.1: Which problems must be addressed?

Q2.2: Which problems are addressed by a desirable solution?

Next, the established values are used to set up design criteria. This stage translates the established design values from stakeholder groupings and the problem analysis into effective criteria for evaluating design alternatives to be produced. Conducting this stage prior to the creation of design alternatives effectively reduces the risk of design fixation [4]. The creation of the design criteria complements the design requirements drafted in Table 2.4 by providing methods for comparing the desirability of certain design alternatives, rather than the acceptability.

Q3: Which criteria are effective for generating and evaluating different design alternatives?

Q3.1: Which design criteria can be extracted from the established values?

Q3.2: How can the established criteria be weighted according to their importance to the research and design goal?

Q3.3: Which method is effective in comparing qualitative and quantitative criteria?

The fourth research question focuses on the generation of design alternatives, following the modeling of the current situation. This step is conducted by implementing various guidelines in pursuit of the design criteria and fulfilling the requirements. Various designs, such as a roundabout, may receive several design alternatives with alterations, as they may perform drastically differently. A preselection of more promising designs is necessary to ensure feasibility of the next step within the available timeframe.

Q4: Which intersection designs compose an inventory of possible solutions?

Q4.1: Which intersection designs are feasible within the project area?

Q4.2 Which alternatives can be excluded via a preselection of more promising designs?

Having determined an inventory of viable solutions, an evaluation of the alternatives must take place. This is done using the program *PTV Vissim*, combined with the open-source SSAM. However, this program may pose limitations depending on the design criteria set. Therefore, an alternative method must be determined, depending on the criteria. For example, measuring the area footprint of the intersection is difficult within the program, so instead scaled drawings are created to measure the areas. Finally, a comparison of the alternatives considering the criteria is made. Depending on the result of this comparison, either a second iteration of the design cycle would be necessary, or a final recommendation can be drawn. In either case, due to the time limitation of the project, a final design recommendation is formulated based on the conducted analysis. This recommendation may be in the form of a single final design, but it may also include added alternatives.

Q5: What is the final design recommendation?

Q5.1: How effective is PTV Vissim in modeling the design alternatives?

Q5.2: Which design criteria cannot be evaluated using PTV Vissim? How can they be evaluated?

Q5.3: How does each design alternative perform in light of the design criteria?

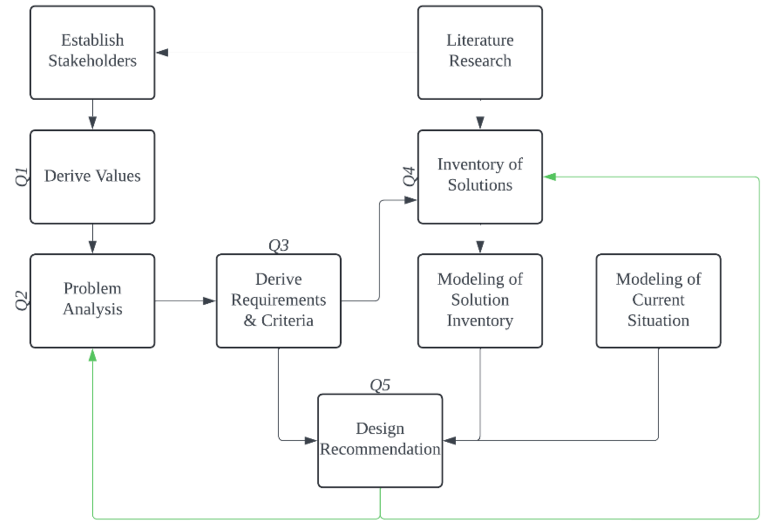

Figure 2.2: Research Methodology. Created using Lucidchart.

2.2 Project Context

In the 1960's, the universities in the German city Münster constructed various facilities in the northwest of the city to expand existing facilities, as well as house new facilities [5], [3]. Although several buildings remain in the city center, a wide variety of faculties are currently located in a congregation around the *Coesfelder Kreuz* [5]. Running north from this intersection is the *Corrensstraße*, which weaves through the center of the various university buildings. This stretch of road is shown in Figure 2.3.

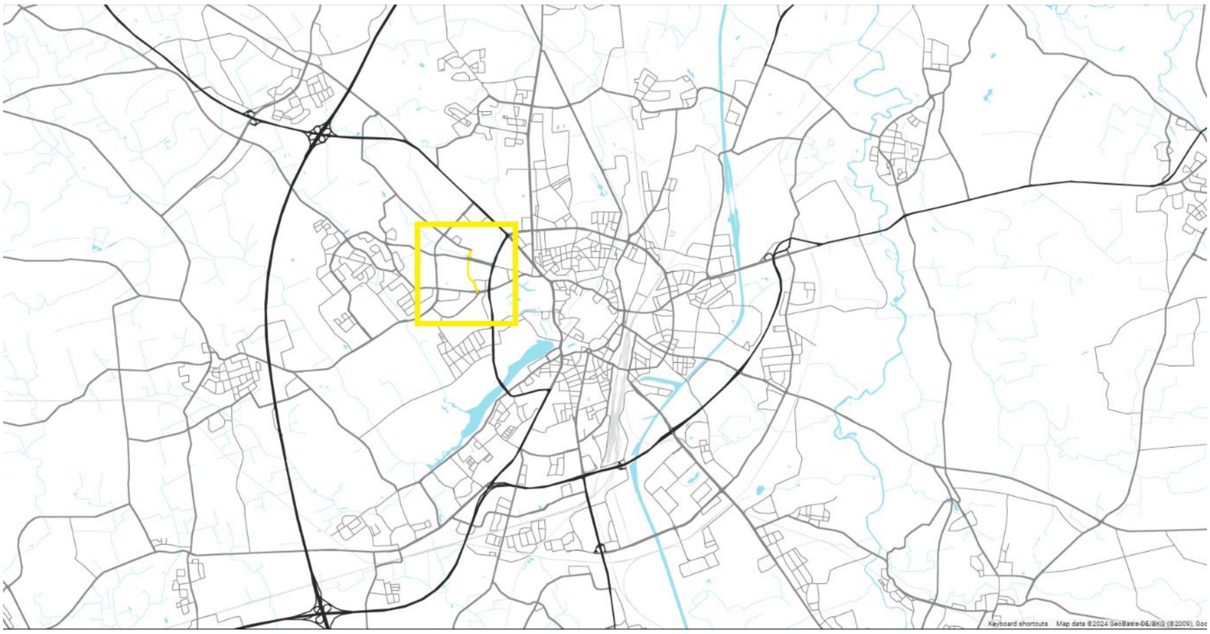

Figure 2.3: Map of the Corrensstraße in the context of Münster. Adapted from Berdén, 2017.

2.2.1 The Current Situation

At the northern end of the university buildings, the *Corrensstraße* crosses another major connection towards the city center, the *Henriette-Son-Straße*. This intersection was constructed in the 1960s, together with the campus buildings and is shown in Figure 2.4 [3]. In communication with the municipality of Münster, this intersection requires a redesign in the near future [3]. For this redesign, a reduction of capacity for cars and increase in safety for non-motorized users is expected, as well as accommodating the planned urban developments in the region [2].

In accordance with the perspective on mobility of the 1960's, the transport connection to the new area was designed with the expectation that most students commute to the university via car [3]. This expected situation never occurred, and recent developments in sustainability and fuel prices have accelerated the modal shift away from the automobile in the region [3]. Consequently, the intersection is drastically over dimensioned, while recorded traffic counts at the intersection are continuously decreasing (See Figure 9.1). The current daily traffic counts summed per link are overlayed over the satellite image in Figure 2.5. Detailed traffic counts separating different users and travel directions are presented in the Appendix in Figure 9.5. With planned developments in the area around the intersection, certain traffic loads are expected to increase slightly, however they will not reach near the planned capacity of the intersection [2], [3].

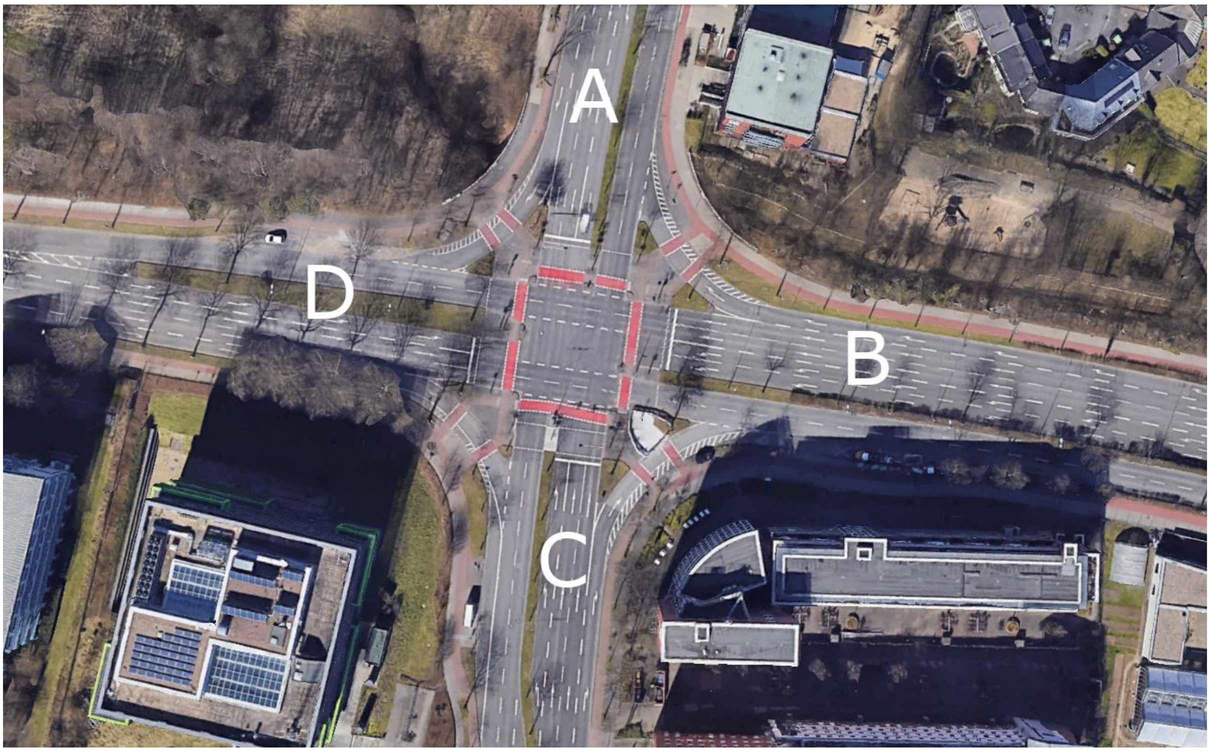

Figure 2.4: Satellite image of the intersection. Retrieved from Google LLC, 2022.

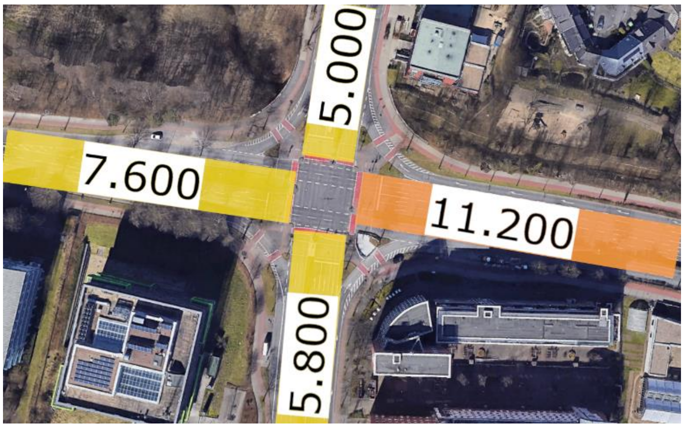

Figure 2.5: Traffic counts per link. Adapted from Google LLC, 2022.

2.2.2 Projected Developments

Although an over dimensional intersection may not prominently cause problems similar to its under dimensioned counterpart, the crossing composes a fundamental aspect of the *Correnssstraße*, which carves a divide through the modern science campuses of the universities of Münster. In the pursuit of a novel vision for several areas within the urban environment of Münster, the Münster *Modell Quartier* (MQ) Plan was adopted, consisting of five different urban development projects, one of which is the Knowledge Quarter within which the intersection is located. [2]. The specific goal for the campus Knowledge Quarter is to create an area of integrated land use to bring life to the area during semester breaks and evenings [3]. To do so, a major consideration goal is the reduction of traffic along the *Corrensstraße*, instead diverting cars to a nearby parking garage to reduce the barrier which the wide boulevard currently creates [3]. Alongside this reduction, the construction of a *Science Boulevard*, a car-free corridor linking the science campuses to the city center, is planned to traverse through the intersection along the North-South link [3]. Nevertheless, the intersection in question will certainly remain of importance, with the municipal traffic prognosis forming the baseline for the creation of the design alternatives to be created as a product of the thesis project [2].

The two different traffic prognoses are calculated as consequences of the individual developments of the *Modell* quarters *MMQ1* and *MMQ2* [2]. They are created as a combination between the projected traffic demand changes by the year 2035 and the influence which the urban development projects have. It is not disclosed whether this prediction takes into account any changes in road geometry and the thereby associated increases in travel delays. The difference between the prognoses in the intersection of question is minimal, and therefore only one combined prognosis is considered. The final presented prognosis is therefore a combination of all three factors and is shown in Figure 2.6.

In addition to the summated traffic counts on each of the links in the near region, several adaptions made to the road network are elaborated, and the characteristics of the traffic and their specific origins and destinations are provided in the document [2]. A key modification taken into consideration within the prognosis are significant traffic calming measures in the *Corrensstraße* in the form of a bicycle road. Another aspect to be noted within this planning is the *Horstmarer Landweg*, the road to which the northern link of the intersection leads. This road is projected to be faced with a significant increase in traffic, largely due to users taking a detour towards the *Steinfurter Straße* due to delays following congestion on the main roads [2]. This traffic demand is incompatible with the current road geometry and traffic calming measures in place to function as a cycling road [2].

The projected flows displayed in Figure 2.6 unfortunately are internally inconsistent through the project intersection, as all other three links fail to summate up to the expected traffic on the eastern link (16,200) veh/d. The reason for this inconsistency is not disclosed. Nevertheless, an approximation of the different directions is made, based on the observed traffic counts, the information provided adjacent to the report, and a brief iterative optimization to achieve near internal consistency. To ensure the reliability of results, a sensitivity analysis of the total travel demand is made in Section 5.

The projected O-D matrix is presented below in Table 2.1.

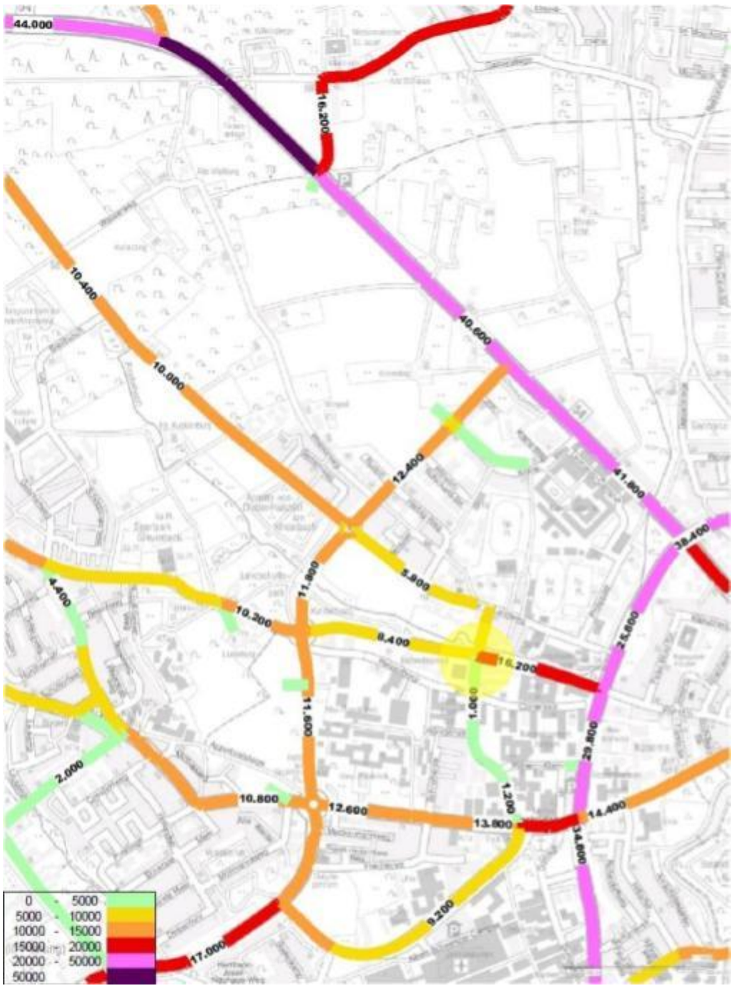

Figure 2.6: Traffic prognosis considering MMQ1 and MMQ2 developments, with the intersection marked in yellow. Adapted from [2].

Table 2.1: Extracted OD-Matrix for the intersection.

	A	B	C	D
A		2 000	200	20
B	3 700		350	4 500
C	100	300		16
D	15	4 000	50	
Prognosed Total	5 800	16 200	1 000	8 400
Estimated Total	6 035	14 850	1 016	8 601
Accuracy	0.96	0.92	0.98	0.98

The hourly values can be approximated to appropriately model the intersection. This is done for every hour of the day, rather than merely the peak hours, as the key criteria are not travel delays, but rather the safety of the users. Consequently, the investigations by Kim et al. [6] and Weijmermars & van Berkum [7] are used to extract daily distributions of traffic in urban areas. The process and resulting hourly OD matrices are shown in Table 9.2. A visualization of the peak distribution of traffic is shown below in Figure 2.7.

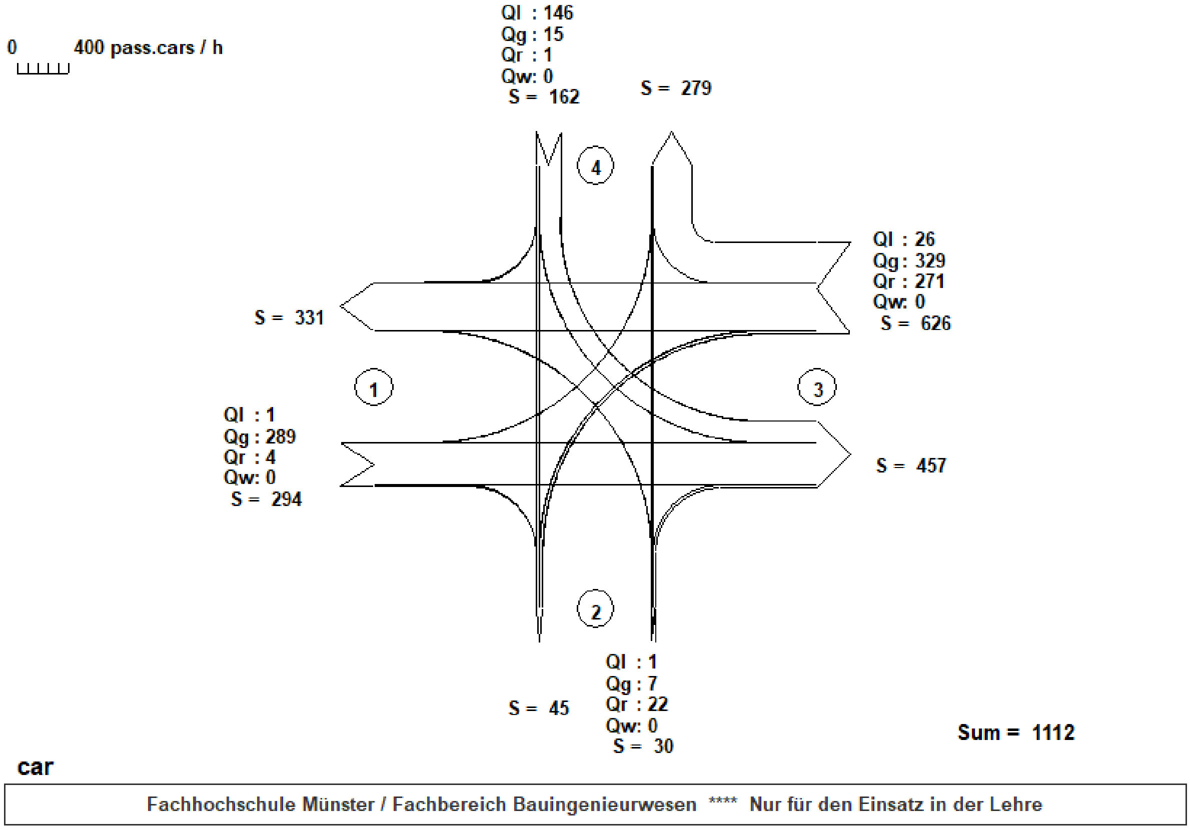

Figure 2.7: Peak distribution of traffic flows 16:00 - 17:00. Created using Kreisel [8].

Finally, the projected municipal plans also account for specific cycling routes. One of these routes will run across the intersection, in conjunction with the *Science Boulevard* [2]. Its relevance to the rest of the cycling infrastructure is seen in Figure 2.8. This link will be converted into a bicycle road. Accordingly, the bicycle counts are expected to increase by a baseline of 21% [9]. As an addition, the consideration of the bicycle highway to the north, modifications being made to the availability of car parking near the university buildings [3], and the high probability of latent demand, an increase of 50% in bicycle traffic is used in the simulations. The sensitivity of the results to this assumption are examined within the sensitivity analysis prior to a final design recommendation to ensure that this assumption does not drastically affect the results.

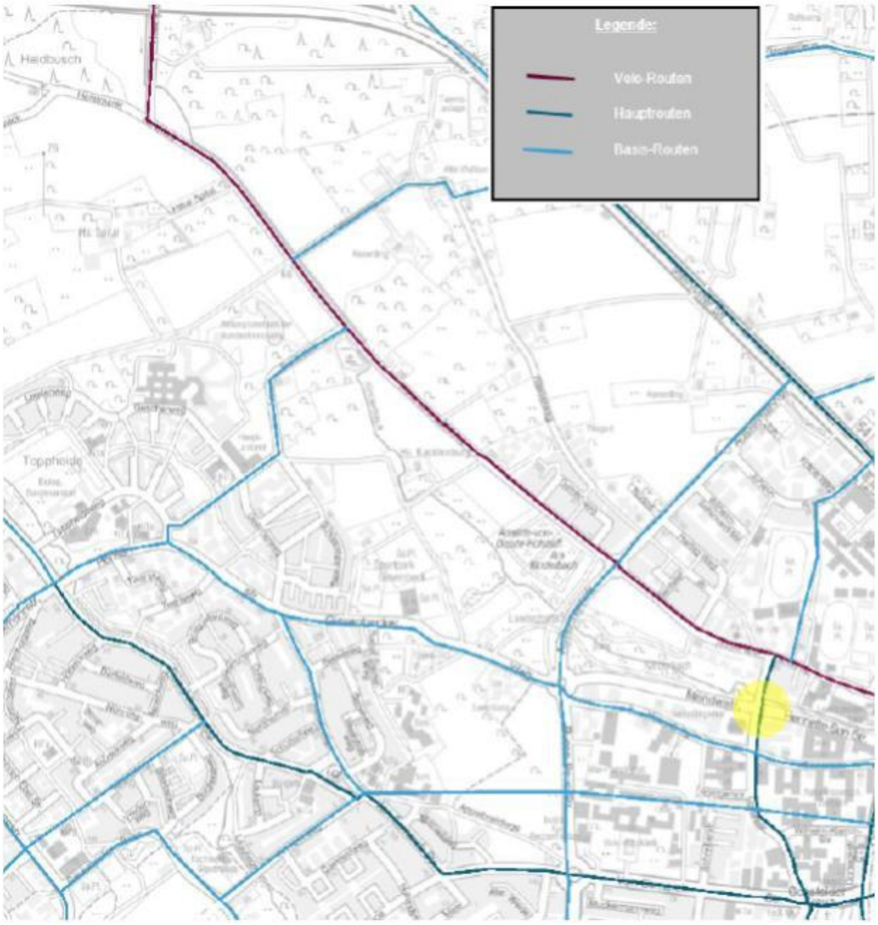

Figure 2.8: Current and planned bicycle routes. Dark blue signifies bicycle highways. Adapted from [2].

2.2.3 Project Stakeholders

A good civil infrastructure design must consider those with a stake in the project to be successful. Various definitions of stakeholders are used in differing contexts; however, this project will consider those who are affected or can affect the project as stakeholders. In this section, a list of stakeholders of the project is identified, together with their characteristics and values relevant to the project.

A list of the identified stakeholders, together with their characteristics and values is shown below in Table 2.2. In Section 3, these stakeholders are then organized according to their power and interest, respectively to allow assigning the values to the criteria derived from the values.

Table 2.2: Stakeholder inventory and values.

Stakeholder	Characteristic	Values
Municipality of Münster	The municipality has the desire to redesign the intersection and has the authority to specify a design. It is also responsible for the drafting of the surrounding urban planning, local traffic regulations such as speed reductions or entire access restrictions and determines city- or quarter-wide policies which guide the project design. Additionally, the Municipality's policy states that traffic solutions should focus on	- Accessibility - Compatibility - Suitability - Environment - Safety of all users

	reducing emissions [2].	
Bicyclists	Cyclists traversing through the intersection	- Safety - Convenience - Low time delay
Pedestrians	Pedestrians traversing through the intersection	- Safety - Low attention required
Through traffic	Drivers of private motorized vehicles using the intersection as an alternative road.	- Low time delay - Less unnecessary waiting
Public transportation	In the future, two bus lines traverse the intersection across north-south [2], and one occasional/night bus east-north (E85/N85) [3].	- Low delay during peak hours - Accessibility to stops
Truck drivers	Heavy goods vehicles traversing the intersection. They are characterized by larger turning radii, slower acceleration, and increased braking distance.	- Accessibility in all directions - No tight turns - Sufficient merging time - Sufficient braking time
Residents	There are currently residencies in immediate vicinity to the intersection, and additional housing is planned in the quarter [2].	- Low noise pollution - Low air pollution - Accessibility to car parking - Pleasant environment
University students/ professors	Students and professors alike require barrier-free access to the university buildings.	- Accessibility to buildings - Environment
Environmental organizations	Environmental organizations defend the environment and gain influence through the support from large groups of people and companies.	- Environment - Low pollution levels - Consideration of biodiversity - Incorporation of nature

2.3 Previous Studies

Throughout the early history of vehicular infrastructure systems, a key focus was placed on increasing capacities to accommodate an ever-increasing number of vehicles on roads. More recent environmental movements in Europe have, in parallel, sparked movements towards the calming of motorized traffic in urban environments [10]. The traditional traffic calming measures in Germany are since characterized by the restriction of cars using – for example – speed bumps, a reduction of road width, or the introduction of 30 Zones with right-before-left priority at every intersection [10]. Although this wide range of solutions has been met with varying degrees of success, implementations of capacity reductions have been primarily limited to road links, whilst research into the intersection of roads is primarily focused on the expansion or maximization of capacity. However, in theory the reverse of measures to increase the capacity of an intersection should lead to a reduction of capacity.

Reductions in intersection capacity are often presented as outcomes of certain interventions and research, because of the prioritization of other methods of transit. An example of such an intervention giving priority to busses and cyclists at the expense of private cars is designed and examined by Høsser in his master's thesis published in 2017 [11]. Here, the right of way is given to public transport primarily, followed by cyclists through a traffic circle. Consequently, the magnitude of inconvenience to cars is entirely dependent on the number of busses and density of cyclists. Without the implementation of signalization, it is not workable to remove this dependency due to the fixed priority ruling. Hence, the insights gained from this intervention, as well as similar ones, provide valuable input for the potential of a non-signalized intersection design.

In light of the third environmental movement [12], the term *Verkehrswende* was coined in Germany to represent a fundamental shift in mobility infrastructure from private vehicular transit fueled by fossil fuels to a variety of more sustainable options [13]. Due to the broadness of the concept, a wide range of solution approaches have been and are being implemented in regions across the country. One of these approaches consisted of an analysis of accidents at intersections and a consequent drafting of a guideline for infrastructure planners concerning "The Optimal Intersection" for cyclists in the region of Hannover [14]. Another approach takes international inspiration from the Netherlands, with the implementation of "Dutch-style" intersections, for example in Darmstadt [15]. Both techniques aimed at implementing the *Verkehrswende* incentivize the usage of active transportation through the intersection's design providing protection and priority to cyclists. As an addition, *Region Hannover,* in collaboration with the local police, investigates extensive statistics about accidents involving cyclists to aim designs at reducing the quantity of accidents [14]. In parallel, *Alshehri et al.* provides a baseline for a design that mitigates the consequences of eventual accidents by performing an analysis of the factors influencing crash severity [16].

To be able to quantify the safety of the intersection designs, however, guidelines are insufficient. Therefore, SSAM, a method developed by Gettman & Head in 2003, is used to determine proxy safety measurements derived directly from the microsimulation models of the alternative designs [17]. Although this method cannot be used to directly measure the safety of the users, it has been determined to be reliable in estimating the potential conflicts within an intersection and a reliable option for thereby comparing the safety of different alternatives, as well as offer insight for improving designs by Astarita et al. [18]. The safety measures considered in this project are the Time-to-Collision (TTC), the Post Encroachment Time (PET), the speed difference between users (ΔS), and the deceleration rate (DR). They are each determined as follows:

$$TTC = \frac{d}{V_f - V_l}$$

Where:

d is the distance between two vehicles.

V_f and V_l are the speeds of the following and lead vehicles, respectively.

The TTC is a continuously changing variable, wherefore the minimal value during two vehicles' interaction is used as the critical Time to Collision [18]. The TTC safety proxy is developed in [19] and [20]. Consequently, a lower TTC suggests a higher probability of collision, and therefore a lower safety [17].

The PET, defined by [21], is the time between an initial road user exiting a zone of conflict and the next user entering the same zone [18]. Like the TTC, a lower PET suggests a lower safety [17].

The speed difference between users is defined as the difference between the highest maximum speed of one of the two users in the interaction and the minimum speed of the other user. This measure is important, as two vehicles traveling at high speed in similar directions pose a lower risk than a fast-moving vehicle and a pedestrian. Therefore, a higher ΔS indicates a lower safety.

Finally, the deceleration rate is defined as the initial deceleration rate required to avoid the conflict [17]. This measure can be used to estimate the severity of the conflict, and thereby the possibility that a collision does occur, such as when a driver is paying less attention.

2.4 Design Problems

Upon inspection of the intersection, several problems are already identified. In this section, the intersection is regarded from the perspective of the three main users, and thereby a more elaborate problem analysis is conducted. In addition, a set of other problems are identified, including the perspectives of the non-user stakeholders.

2.4.1 Problems for Bicyclists

The exploration of problems is primarily conducted through observation during sight visits and supported by literature research regarding bicycle safety and preferences. The pre-existing problems for bicyclists in the intersection can be categorized into two groups, consisting of inconveniences and dangers. A graphical representation of these problems is provided below in Figure 2.9, with dangers depicted in red and inconveniences in yellow.

In the figure, the path that should be taken by bicyclists is shown in yellow, with a striped, yellow line depicting a straight path from their origin to the intersection. The detour shown on every corner shows an increased travel distance, as well as tight corners for which cyclists must drastically slow down. This deceleration causes an increased effort to accelerate after the crossing and leads to a delay which may cause the cyclist to miss a green light. Therefore, the ‘snaking’ of the cycling lane through the intersection constitutes the major problem of inconvenience.

To avoid these inconveniences, multiple site visits proved that cyclists tend to take a shortcut diagonally across the pedestrian crossings. Aside from the threat to pedestrians caused by this deviation, car drivers turning right are faced with an unknown whether a cyclist will slow down or not. At the same time, the right turn slip-lane for cars means that vehicles turning right maintain a relatively high speed [14], incentivizing some drivers to speed up to make the turn before the cyclist reaches the intersection. Given that over 47% of urban accidents involve cyclists, and nearly 60% of casualties[1] in urban accidents are cyclists [14], most of which are a consequence of accidents with cars [14], this location is a key to improving the safety of cyclists in the intersection.

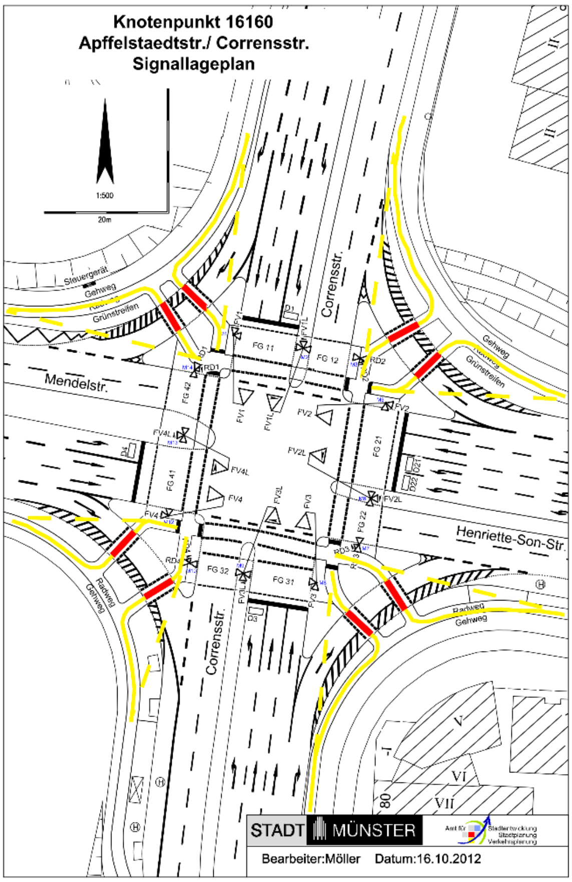

Figure 2.9: Dangers and inconveniences to bicyclists in the intersection.

2.4.2 Problems for Pedestrians

Like bicyclists, pedestrians traversing the intersection are faced with multiple inconveniences and dangers. Although pedestrians tend to be involved in far fewer accidents than cyclists or motorists at merely 4% of all urban accidents [14], their safety within the intersection should not be neglected. A higher mobility and ability to react means that pedestrians can avoid dangerous situations more easily, however the prevalent issues within the intersection lead to a lower perceived safety and comfort. These issues are outlined below and presented in Figure 2.10.

Pedestrians entering the intersection in any direction other than turning right must cross cyclists turning right. This conflict is shown in the figure in cyan. It is particularly dangerous when pedestrians are coming from the same direction as the cyclist, as a safe crossing requires the pedestrian to turn their head 180º before walking. Although the potential for collision is low, a pedestrian must make this motion before crossing to avoid collisions, causing an inconvenience.

[1] Casualties refer to persons killed or heavily injured because of the accident.

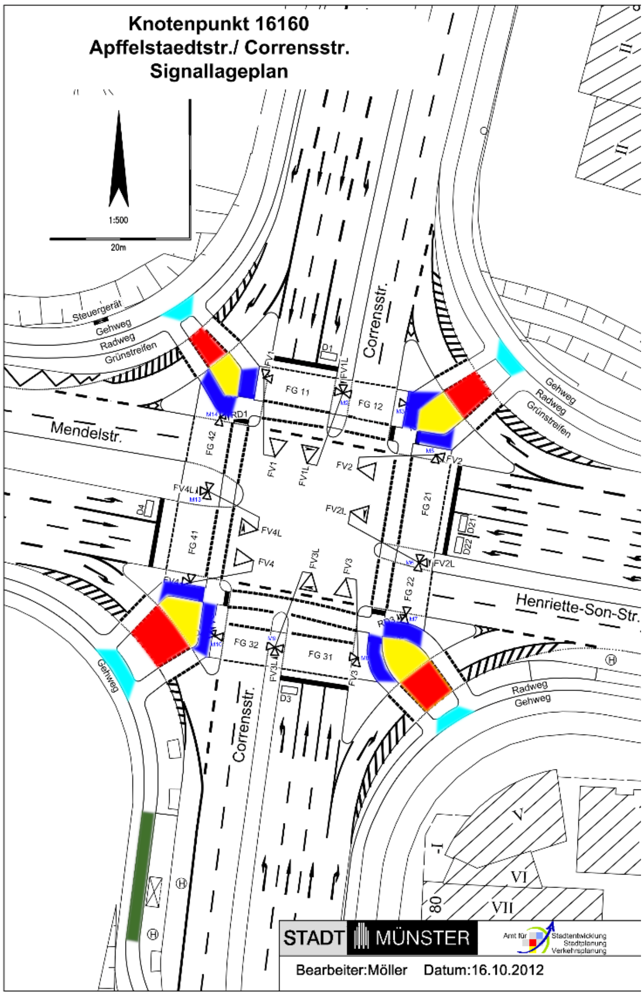

Figure 2.10: Conflicts between pedestrians and other users in the intersection.

Secondly, the pedestrian must cross the motorized slip-lane to enter an island. This crossing is not regulated by a traffic light, and whilst cars must yield to cyclists crossing in this location, there is no clear signage for pedestrians. Consequently, cars will often yield to pedestrians, but not in every instance. This creates a dangerous situation for pedestrians that assume a car will yield, but also to cars which to yield and have a trailing car assuming they will not. This conflict is shown in red.

Next, pedestrians enter the island, surrounded by two cycling lanes before they can reach the signalized crossing of the main road. As mentioned above, cyclists often cut through this island to avoid having to slow down for a tight turn, which causes an inconvenience and lacking feeling of safety for the pedestrian. The island is shown to be highlighted in yellow.

When approaching the signalized light, a pedestrian must once again cross the cyclist lane. In one of two directions, this area is reserved for cyclists waiting at a light to cross themselves, meaning that a pedestrian may have to weave through stationary cyclists to reach their light. Additionally, if the pedestrian light is red, they may consider waiting inside the pedestrian island, as the space between the cycle path and the active road is small and the vicinity to rapidly moving vehicles can be dangerous. These conflicting areas are shown in blue.

Finally, a soft conflict exists between bicyclists and pedestrians in the south and north of the intersection at the bus stops, where pedestrians must cross the bicycle lanes to reach the stop. Although cyclists have priority in these locations, a busy bus stop could lead to a crowded area and conflicting space between the two users. Although rulings show that cyclists must be wary in situations like these, it poses a safety risk to pedestrians. This area is shown in dark green in the south.

2.4.3 Problems for Cars

Motorized users traversing the intersection face minimal problems with the current state. Nevertheless, a handful of problems related to the motorized usage of the intersection are identified. These are centered around inconvenience and a lack of necessity for certain elements. Figure 2.11 depicts the identified problems.

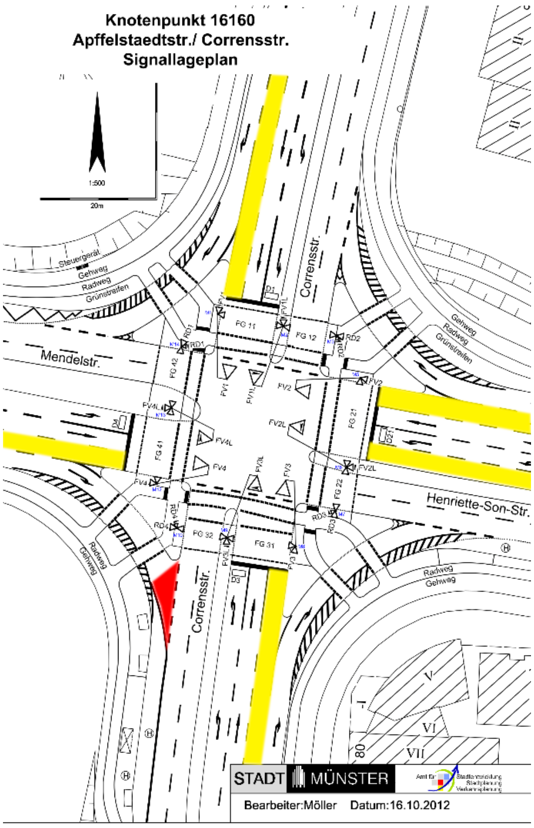

Figure 2.11: Identified problems for motorists in the intersection. Yellow denotes unnecessary lanes, whereas red shows a conflict.

As elaborated upon by the municipality, the capacity of the intersection is too large. Therefore, the lanes marked in yellow are unnecessary space for motorized vehicles, which increase conflict potential within the intersection. This is because vehicles merge onto other lanes to avoid one another and traverse the intersection more quickly, decreasing the safety of the intersection. Another example are the two left-turn lanes originating in the east. Together with the removal of these features, the exiting lanes can also be deemed unnecessary, as only one lane will be pointed in any given direction at a time. While the lanes increase the capacity of the intersection and marginally decrease the travel time, they are entirely unnecessary regarding the traffic saturation flowing through the intersection.

Another problem is identified in the south of the intersection. The right-turn slip lanes have a space reserved for motorists waiting to enter the exit lanes after the bicycle crossings. However, in the southern link, there is a bus stop immediately after the intersection, for which buses must merge over into a third lane to stop. Thus, waiting motorists must wait further back to allow for this movement. In doing so, they may restrict the cyclists' ability to cross. Due to the rarity of a bus crossing the intersection, cars therefore stop further ahead and cause a problem for bus drivers.

2.4.4 Other Problems & Summary

A handful of problems related to the intersection are also not related to any of its users. These problems relate to wishes of the municipality or environmental problems. One wish of the municipality lies in the reduction of the *Correnssstraße* to allow for easier passage of pedestrians and incentivize bicycles to use the route more [3]. This aligns well with the projected traffic demand on the road according to measures that will be taken. This expectance must thus be mirrored in the intersection, for which the current connection in the south is not suitable. Instead, a single lane travel in either direction is necessary to connect to a cycle road. Additionally, an environmental wish of the municipality lies in the reduction of the intersection's footprint, thereby increasing the area accessible by foot and dedicated to greenspace. Another major problem the intersection poses when confronted with the plans of the municipality is the *Science Boulevard*, which is a footpath planned to cross the intersection along the north-south link. This conflicts with projected major traffic flows which will be coming from and going to the east. Finally, a planned cycleway will pass just north of the intersection along an east-west route. Hence, the bicycle connectivity to this regional cycleway should be given a priority to connect the major educational facilities to the regional link.

There are other additional environmental issues raised by the current intersection which are not directly reflected in the problems highlighted by the municipality. Firstly, the lack of activated signaling means that most traffic is required to come to a complete stop when traversing the intersection, leading to excessive emissions created. Secondly, the intersection restricts a natural connection between green and blue infrastructure to the northwest and the other three sides of the crossing. Currently, the roads simply bridge over the *Kinderbach*, a small river flowing underneath the northern link of the intersection. It is hardly noticeable to all users, and there is also no connection of the greenery to the walking paths along the intersection. This creates a hostile environment for pedestrians by remaining in the vicinity of the road, rather than connecting directly to the nearby *Annette von Droste-Hülshoff Park*.

The previously established problems in respect to the users, as well as the general problems established in this sub-section, are presented below in Table 2.3.

Table 2.3: Identified problems of the intersection categorized by user and characteristic.

Index	Problem	Characteristic	Description
	Bicycles		
B.1	'Snaking' lanes	Inconvenience	Bicycles must slow down to follow the winding path
B.2	Car crossing	Danger	Soft conflict between cars turning right and bicyclists
	Pedestrians		
P.1	Cyclist crossing	Danger	Soft conflict with cyclists turning right
P.2	Road crossing	Danger	Lack of signaling gives neither mode clear priority
P.3	Cutting cyclists	Inconvenience	Potential conflict with cyclists shortening their route
P.4	Cyclist crossing	Danger	Soft conflict with cyclists in the intersection
P.5	Cyclist crossing	Danger	Soft conflict with cyclists when accessing the bus stop
	Cars		
C.1	Unnecessary lanes	Inconvenience	Unnecessary lanes in intersection entry and exit
C.2	Slip-exit south	Inconvenience	Lacking waiting room that blocks buses or cyclists
	Other		
O.1	Southern connection	Incompatible	New goal aims for a smaller Corensstraße
O.2	Science Boulevard	Unsuitable	Lacking pedestrian safety and convenience
O.3	Bicycle Highway	Incompatible	Lacking cycling infrastructure along planned route
O.4	Overall Footprint	Unsuitable	The asphalt footprint of the crossing is unnecessarily large
O.5	Green & Blue Infrastructure	Incompatible	The roads and crossing currently disregard the present natural infrastructure

2.5 Design Requirements

Following the investigation of the problems in the current state of the intersection, as well as the exploration of future developments to be expected around the intersection, a selection of hard design requirements is drawn. All potential solutions must fulfill these requirements to be considered for further inspection, modification, and comparison. Therefore, only the most basic criteria are included, as the design criteria are established in the following chapter. The hard design requirements are listed below in Table 2.4 and separated according to the sub-categories of accessibility, safety, and legality.

Table 2.4: Hard design requirements.

Index	Requirement
	Accessibility
1.1	Unrestricted access in all four travel directions
1.2	Incorporation of current bus lines 2 and E/N85
1.3	*Science Boulevard* crossing north-south
1.4	Connection to regional cycling route to the north
1.5	Ability to accommodate projected traffic flows under both prognoses
	Safety
2.1	Resolving of all 'dangers' listed in problem index
2.2	Improved non-motorist safety
2.3	Resolving conflict between pedestrians and cyclists
2.4	Clear signaling of priorities
	Legality
3.1	Listed in Appendix (Table 9.3)
3.2	Accessibility for emergency services
3.3	Consideration of eventual changes to legislation

3. Develop: Design Criteria & Solution Set

3.1 Developing Design Criteria

The first step in developing the design problem into workable solutions is outlining certain design criteria. In conjunction with these criteria, a set of design requirements are drawn. Whilst the design criteria are used as a set of 'wishes,' according to which a more favorable design can be chosen, design requirements are limiting conditions, listing aspects which **must** be included in all design alternatives. The design criteria are extracted from the values of the respective stakeholders and the problem analysis, whilst the design requirements are extracted only from the problem analysis.

3.1.1 Importance of Stakeholders

To obtain a useful set of design requirements, a method for establishing the relative importance of the determined values must be used. As the design criteria follow from the stakeholders, a Power-Interest grid is used to organize the stakeholders [22]. Following this step, the values are grouped according to their importance to these stakeholders before receiving a final importance.

As a first step, the stakeholders are organized. In Figure 3.1, all the stakeholders can be seen placed on a 2x2 grid. In this grid, the power over the situation is portrayed horizontally, whilst the interest in the project is shown vertically. The grid is split into four squares; the players are stakeholders with high power and interest, which should closely be considered and consulted, if possible. The context setters should be kept content and considered, but do not require more attention. The subjects should be considered on a more significant level but have little power to enforce their wishes, whilst the crowd should be considered, albeit at a lower priority.

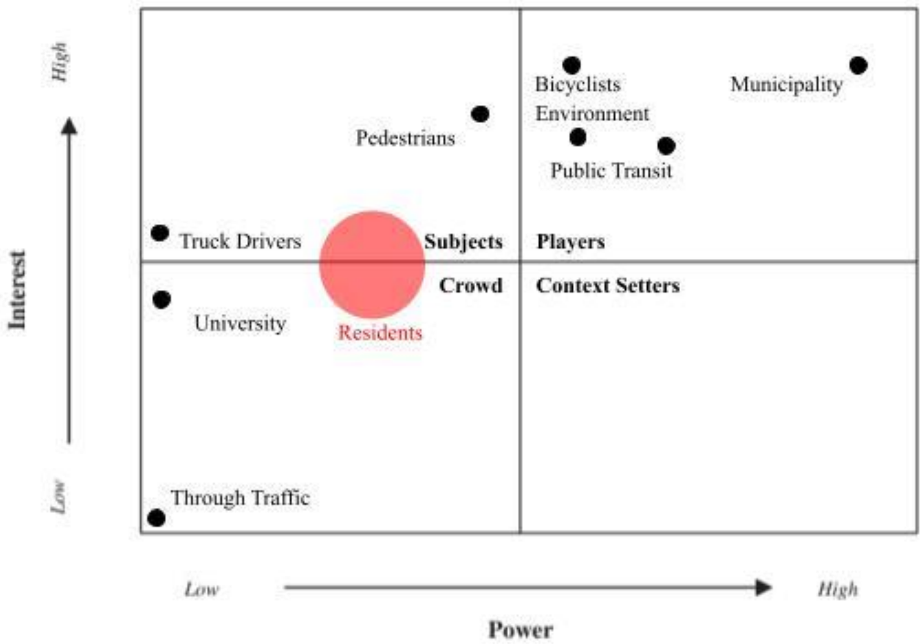

Figure 3.1: Power-interest grid. Adapted from [16].

The municipality is considered as the key player in this project, as they have significant interest and power over the situation. The municipality is placed in the top-right of this quadrant, as they are the client, with full control over the implementation and the organization most interested in changing the current design. Other players include environmental organizations, public transportation, and bicyclists. Environmental organizations have less direct power; however, they show major influence through their strong socio-political backing. Their interest is less specific to this intersection, and instead towards incentivizing cycling and more efficient car usage. Bicyclists have a significant interest in the intersection, as it comprises a key connection to the bicycle highway. They are represented by large interest groups, such as the *ADFC*. The public transportation company is interested in the situation, as three different bus lines will run through the intersection, and they expect to not face delays. They also have significant power, as they are a high priority of the municipality.

Potential context setters include the regional and national governments. However, their policies are implemented by the municipality, and their laws are considered in the design requirements, wherefore they must not be considered as individual stakeholders in the project.

Pedestrians, truck drivers, and some residents are considered the subjects of the project. Pedestrians have a higher power and interest, similar to the bicyclists yet lower. This is because the traversal of the intersection by foot must be accessible via the design requirements, and their representation via the *FUSS e.v.* is weaker than the *ADFC*. Truck drivers are also considered, as they form an essential aspect of the infrastructural supply to nearby buildings. Some residents may have a high interest in the intersection, especially those who reside in the direct vicinity.

Through traffic, university commuters (car), and other local residents are the crowd for this project. These groups have little power over the situation, and, although residents and commuters show relatively high interest in the project, it does not match the interest of a subject. This is because they can easily be satisfied with travel times which are not increased drastically, and all other modifications have negligible effect on their experience through the intersection.

3.1.2 Grouping Values

Finally, before deriving design criteria, the values of the stakeholders are grouped. This allows certain values to gain more significance, especially if they are desired by numerous stakeholders. The values are based on Table 2.2, whilst relative importances of the values for each stakeholder are estimated using available literature, where available. The resulting grouped values are shown in Table 3.1.

Table 3.1: Value groupings.

Value Group	Interested Stakeholders	Importance to Each Stakeholder
User Safety	Municipality Bicyclists Pedestrians All Drivers	Top priority [2], [23] Top priority [14] Top priority [14] Top priority
Environmentally Friendly	Environmental Organizations Municipality Residents	Top priority Top priority [2] Medium [10]
Prioritize Environmental Methods of Travel	Municipality Bicyclists Public Transportation Pedestrians Through Traffic	High [2] High High High Against
Sufficient Accessibility	Pedestrians Truck Drivers Municipality	Very high Low High [2]

Within each value grouping, certain stakeholders view the issue differently. Additionally, a single stakeholder may be interested in various aspects of a value, such as the Municipality's wish to be environmentally friendly by reducing the asphalted area, as well as limiting the CO_2 emissions in the intersection [2]. Therefore, a multitude of design criteria are drawn in the following chapter.

3.1.3 Final Design Criteria

The final design criteria to be used to evaluate the different design alternatives are now extracted from the previous section. To ensure both simplicity for the final evaluation and the ability to objectively score the alternatives, each criterion is split down into its measurable indicators. These indicators are based on data availability and the problem analysis. The methodology for measuring the different design criteria is elaborated upon prior to the evaluation in Chapter 5.

User Safety

Most stakeholders with a high interest in the project place safety as their top priority. The municipality, in alignment with the national goals [23], also places the safety of non-motorized users at a significant priority compared to all other goals [2]. Consequently, the weighting of this criterion is very high. At the same time, numerous methods for estimating the safety of the intersection are required to more effectively be able to evaluate the safety of an alternative. Therefore, the measurements taken by SSAM through Vissim are used as a key input for this criterion, alongside geometric methods such as the counting of conflict points, their respective risks of collisions and eventual angles of collision.

Environmental Performance

The environmental performance of the intersection is reflected in a large variety of potential measures. One aspect lies in the direct environmental performance of the intersection itself. Measures to evaluate this include the percentage of green ground cover, as well as the total area required. On the other hand, the usage of the intersection also results in environmental consequences. One measure of this are the CO_X emissions of vehicles traversing the intersection. Several other measures could be the NO_X emissions, SO, or various PM indicators. Despite the capacity of Vissim also measuring NO_X, the indicator is calculated in a similar manner to CO_X emissions, and would therefore bias the evaluation towards the key influences causing the emissions. Other environmental indicators have been omitted due to feasibility constraints on the methodology and timeframe of the project. The environmental performance of the intersection is a key aspect for the municipality and environmental organizations, making it the second most important design criteria group.

Prioritization of Sustainable Travel

The prioritization of non-motorized users is a central objective of the redesign of the intersection to accommodate the projected changes to the *Corrensstraße* [2], as well as aid in accelerating the mobility shift towards more sustainable modes of transit [23]. To measure the prioritization in terms of travel delay through the intersection, Vissim features a built-in measure of travel delay. This can be used to evaluate the delays to cyclists and busses and estimate delays to pedestrians. As the physical distance is a crucial factor for pedestrians, this criterion is also measured geometrically. The other form of prioritization is the space reserved for these specific modes. This can be measured with the total area reserved for bicycles, pedestrians, and busses. The prioritization of sustainable travel certainly affects the travel delays through the intersection, and would therefore also affect traffic flows through the intersection. This second degree effect, however, is not considered. This is the case due to time constraints, as well as the request of the municipality to not consider other network links as possible detours. Instead, the accessibility design criteria ensure that delays are kept within a reasonable degree. Though not a top priority, this criterion is important to a wide range of stakeholders.

Accessibility

The accessibility criteria reflect the ability for the continued usage of the intersection. A large quantity of accessibility measures is already included in the design requirements. Therefore, the remaining criteria include the travel delays to private vehicles, as well as the maximum queue of each intersection. These criteria are essential to ensure the functioning of the intersection as an integral part to the infrastructure of Münster. These criteria are weighted low, as certain delays are acceptable and even encourage a modal shift [1].

This concludes the various indicators of the respective criteria. Table 3.2 below shows these objective indicators, their weightings within each criterion, and the weightings of the criteria themselves to finalize the design criteria. The procedure using which the criteria are made use of is elaborated upon in Section 5 on Page 46.

Table 3.2: Final design criteria.

Index	Criterion/Measure	Optimal Value	Unit	Weighting
S	User Safety			9
S.1	Average Conflicts	Lowest	h^{-1}	6
S.1.1	TTC	6	s	7
S.1.2	PET	5	s	3
S.1.3	ΔS	Lowest	$m\ s^{-1}$	3
S.1.4	DR	Lowest	$m\ s^{-2}$	5
S.2	Points of Conflict	Lowest	-	5
S.3	Conflict Danger	Lowest	-	3
S.4	Degree of Conflict Motorized	0 [24]	°	2
S.5	Degree of Conflict Bicycle	60-90 [25]	°	4
E	Environment			7
E.1	Vegetation Cover	Highest	%	3
E.2	CO_X Emissions per Peak Hour	Lowest	$g\ h^{-1}$	3
E.3	Total Area	Lowest	m^2	3
P	Prioritization of Sustainable Travel			5
P.1	Average Cyclist Delay	Lowest	s	7
P.2	Average Bus Delay	Lowest	s	5

P.3	Area for Sustainable Travel	Highest	%	1
P.4	Average Pedestrian Walk Time	Lowest	s	4
P.5	Total Pedestrian Detours	Lowest	%	2
A	Accessibility			3
A.1	Average Motorist Delay	Lowest	s	2
A.2	Maximum Queue Length	Lowest	m	5

3.2 Initial Design Alternatives

In this section, a large variety of potential intersection designs are introduced and briefly discussed to obtain a broad inventory of feasible designs, according to the design requirements.

3.2.1 Signalized Intersections

Minimal Intervention

The minimal intervention alternative sees the intersection remain equal to its current state. The removal of certain lanes, such as the two left-turn lanes and the right turn slip-lanes reduce the overall footprint of the intersection, allowing for added space for non-motorized users. The result is a generic signalized four-way intersection. The following alternatives build as additions to this option.

Dutch-Style Cyclist Priority

An alternative to the current method of indirect left turns for bicyclists, the Dutch method allows cyclists to cross the intersection together with cars.

Modal Offsetting

This alternative gives cyclists and pedestrians green and red before the motorized users. In doing so, the waiting non-motorized users begin traversing the intersection before cars can start turning right, making a clash less likely. At the same time, the non-motorized users have a red light before the cars must stop, allowing for a brief window of safe right-turning for cars in case there is a high non-motorized usage.

Incomplete Signalization

Incomplete signalization sees the major traffic flows continue to have traffic signals, whilst the lights are removed for minor links. Studies find mixed results regarding increases in safety, whilst capacity is increased, and maintenance decreased [26]. Although minor links do not have lights stopping them, a variant of this intersection also features sensors triggering other links to have full red to allow exiting, which allows the busses to easily cross the intersection without major delay [26].

3.2.2 Circular Intersections

Small Roundabout

The small roundabout is a circular intersection, wherein the entering traffic must yield to the traffic within the roundabout, flowing in an anti-clockwise direction. The small roundabout is characterized by a small radius, with a fixed center island and rumble strips over which longer vehicles can traverse to enable the maneuverability. Bicyclists are joined onto the road together with motorized vehicles prior to entering the roundabout and traverse the roundabout just as motorized vehicles do. Pedestrians can cross the roads at each entrance/exit of the roundabout using pedestrian crossings with a middle island.

Segregated Roundabout

With similar road rules to the small roundabout, the segregated roundabout has separated bicycle lanes around the circular intersection, crossing the entrances and exits adjoined with the pedestrians.

Turbo Roundabout

Expanding on the capacity of the segregated roundabout, a turbo roundabout features a second lane that may connect the principal traffic flow to accommodate a higher traffic load.

Traffic Circle

A traffic circle retains the circular shape of the intersection, but resembles a circle of T-intersections, which can each be regulated differently and separately. This means that one of the links may have traffic lights, whilst another keeps a right-of-way principle.

Dog bone Roundabout

The dog bone roundabout assumes a peanut shape of two adjoined roundabouts. They are effective for connecting roads which do not perfectly intersect at one point and slow down users.

Oval Roundabout

The oval shaped roundabout favors one crossing direction of traffic whilst posing an inconvenience to traffic from the other two directions. The oval shape has a lower effect on the speed of vehicles in the principal direction, whilst significantly slowing down vehicles entering or leaving the longer sides of the intersection.

3.2.3 Fixed Priority Intersections

Restricted Turning

By implementing a hard median crossing, the intersection in an east-western direction, vehicles on the *Corrensstraße* are forced to turn right into the intersection, and left turns are entirely prohibited. Thereby, a fixed priority is feasible across the entire intersection. To allow non-motorized users to cross the intersection towards the north and south, as well as the ability for buses to cross in the same direction, priority ruling favoring the *Correnssstraße* is required. The surrounding network is able to divert traffic to its destination.

Southern Stop Sign

Rather than a yield signage, the *Correnssstraße*, entering the intersection from the south, could also be served with a stop sign, given the traffic calming measures in place and the low traffic count. This could increase the safety of the intersection, forcing drivers to take more time to evaluate the surroundings and bicyclists before entering the intersection.

3.2.4 Other Individual Design Aspects

Raised Pedestrian & Bicyclist Crossings

A slightly elevated crossing for non-motorized users leads to a significant reduction in speed of motorized users, an increased walking speed for pedestrians, and a significantly increased yield rate [27]. This intervention would then, naturally, also decrease the capacity of the intersection by reducing the speed of the vehicles by 50% [27].

Curb Extensions

Curb extensions feature a narrowing of the roadway approaching the intersection, effectively reducing the distance pedestrians must walk on a road. They thereby increase safety, whilst also slightly reducing the speed of motorists due to a thinner perceived road [28].

Protected Intersection

A protected intersection features a hard separation between the bicyclists and pedestrians and the cars by including a curb between the cycle path and the roadway. Although the effect of modal separation is highly dependent on the specific implementation, it is found to decrease turning speeds and often increase the amount of attention paid to bicyclists within the intersection [29].

Bright Road Markings

The usage of red markings for bicycle paths yields mixed results in view of the safety of the cyclist. In general, the optimal implementation features the usage of red marking of **only one** crossing in the intersection, usually the link with the highest potential for accidents, however the results also show an effectiveness of marking all crossings in red [30].

4. Create: Refined Solutions

Having determined the criteria, requirements, and potential elements of the design alternatives, this chapter focuses on the explicit creation of the alternative designs. This is done by first establishing which aspects of the design alternatives are realistic to perform well, and which parts can be omitted. This is followed by the geometric creation of the design alternatives, and their modeling in *PTV Vissim*.

4.1 Solution Preselection

Due to the vast array of design alternatives, several must be selected to be evaluated using the framework previously established. Additionally, the alternatives to be chosen from do not include the other individual design aspects listed in 3.2.4, as these are compatible with all design alternatives, and the selective implementation may skew the results of the investigation. Instead, the addition of each of these measures to the final design alternative is to be evaluated in Chapter 5: Evaluate.

The minimal intervention scenario will be included in the investigation, acting as a minimum cost intervention to accommodate the design requirements. This design features four traffic light phases, as left turns from the east and west are disallowed.

Partial signalization, whilst a viable alternative for the southern connection of the *Corrensstraße*, poses a complex situation regarding the northern link, as this traffic demand is unlikely to be met by a yield signage. This solution is therefore excluded from further analysis.

Due to the traffic load, the implementation of a mini roundabout is unrealistic and may cause bottlenecks due to the previous road geometry. Despite heavily skewed traffic loads on the different links, a small, segregated roundabout will be tested. This is because it also provides more safety to cyclists traversing the intersection while potentially reducing vehicle delays during off-peak hours. A traffic circle and a dog bone roundabout are not suited for the situation, as they are often counter-intuitive to traverse and may cause added accidents at a 90-degree junction.

Finally, two variations of fixed priority intersections will be investigated. Firstly, an option only allowing turning right from the *Corrensstraße*, and restricting left-turning from the east and west. The second variation of such a fixed-priority intersection features the conversion of the *Corrensstraße* into a bicycle street. In both cases, the priority is given to vehicles, pedestrians, and cyclists on the *Corrensstraße*. Although this may seem counterintuitive when inspecting the traffic counts, it allows the major sustainable methods using these links priority across a busy intersection they could otherwise not cross without hassle.

4.2 Modeling Process & Validation

The process undertaken to produce the four design alternative models is comprised of multiple steps. The initial step consists of the conceptualization of each design alternative. Four realistic designs are selected and adapted in consultation with the Municipality of Münster. This paves the way for the geometric creation of the links within *Vissim*. The drawing of links, their respective lane widths, distances between different modal users, and turning radii are created in constant consultation with the legal requirements and recommendation in Table 9.3.

Following the geometric design of each intersection, the traffic input is determined. This input is constant across the different alternatives, except certain O-D links unavailable due to disallowed left turning or straight driving are replaced with the alternative route. Firstly, the modal split of vehicles is set. According to observations of the intersection from 2022, shown in Figure 9.5, the motorized traffic traversing the intersection consists of 96.2% cars, 0.3% buses, 1.1% trucks, 0.6% articulated trucks, and 1.8% motorcycles. This distribution is reflected within the simulation.

Following the traffic vision of the Municipality, the priority of the intersection's design does not lie in accommodating for rush hour traffic, but rather producing a safe intersection suitable for all times of the day [1]. Therefore, the 24-hour traffic prognosis from Table 2.1 is split into hourly traffic demands using aggregated data from two analyses of daily traffic distributions in urban intersections [6], [7]. The final O-D matrices are therefore shown in Table 9.2. This allows for the testing of the models in all conditions they are expected to perform. Due to a lack of bicycle prognoses, their counts are kept constant to the observation in 2022, albeit with a 50% increase. These values are used for the morning and afternoon peaks, respectively. It was assumed that, prior to the morning peak and after the evening peak, there is a very low travel demand for bicycles. Nevertheless, several bicycles per hour were included to ensure the measurement of travel times. For the hours between the peaks, an average is taken between the current morning and afternoon peaks, without including the 50% increase. This aims to emulate the regular travel through the intersection, as well as commuters of off-peak hours. Finally, static pedestrian routes are implemented. Their hourly demand remains constant throughout the simulation and simulates a high foot traffic, as expected to arise due to the surrounding urban developments [2]. This static demand is chosen due to software limitations.

Next, the public transport lines are integrated into the model. They are input as static connections, simulating the pre-existing lines 2 and N85, as well as the planned additional line running along the same route as the line 2. Bus line 2 and the novel line also attend a bus stop just south of the intersection, which is implemented in each model as visible in their depictions below. The north-south bus lines run from 5:45 to 20:15 in 15-minute intervals, and the north-east bus lines run from 21:18 to 23:59 in 30-minute intervals. To simulate the increased pedestrian demand after a bus arrival at the bus stop near the intersection, each bus is considered to have 20 passengers which depart.

Finally, the coordination of the areas of conflict are organized. For alternative 1, this is done by regulating the traffic lights. This process is conducted according to the German guidelines *Richtlinien für Lichtsignalanlagen* (RiLSA) and is shown in Table 9.4 and Table 9.5 [31]. For the other alternatives, the Vissim-internal conflict zones are used to signify the priority of certain links over others.

The different models are then face-validated to ensure their realistic functioning. This is done by increasing the traffic load and observing the behavior of vehicles and their interactions with one another. To ensure the validity of the models, certain modifications had to be made. One of such modifications includes the grade separation of bicyclists on the *Corrensstraße* bicycle road before the intersection, as they would otherwise merge with traffic and use the traffic signals to traverse the intersection, despite these links being restricted for them. Additionally, increased safety distances had to be introduced to prevent vehicles from accelerating into pedestrians occasionally. These safety distances denote the amount of space vehicles provide as buffer space between the front of their car and the conflicting pedestrian or cyclist. Per default, this value is often set as zero, and therefore an additional distance of 1.5 is introduced. However, following several iterations within each design alternative, the behavior of traffic sufficiently imitates the behavior of real drivers, including rare drivers merging too late, most drivers driving slightly above the speed limit, and variations in driving, cycling, and walking speed. As a result, the models can effectively model not only the ideal-conditions behavior within the intersection, but also infrequent mistakes which are often the cause to dangerous situations.

4.3 Refined Design Alternatives

4.2.1 Alternative 1: Minimal Intervention

In the minimal intervention scenario, the same method of handling traffic is used as in the current state. To adapt to the modified traffic counts, it features a heavy reduction in the number of lanes entering and exiting the intersection. The removal of the right-turn slip lanes improves bicycle and pedestrian comfort and reduces the speed at which cars can turn. Additionally, the ability to turn left into the *Corrensstraße* from both the east and west is no longer possible. The surrounding network is expected to be able to accommodate this change, given small detours for each respective route, as explained below. Additional attention is concentrated to the bus stop south of the intersection, with pedestrian access directly to the intersection, reducing the need for pedestrians and bicyclists to cross. The bicycle routes follow alongside the road to improve visibility of cyclists prior to the interaction, before yielding space to pedestrians crossing so that they must not wait on the roadway for cyclists to pass, as well as offsetting the interaction between vehicles turning right and cyclists, to approach a 90-degree collision angle. This further increases the visibility of cyclists to vehicles turning right.

Vehicles attempting to enter the *Correnssstraße* in the southern direction originating from the east are able to either make use of the *Coesfelder Kreuz* and approach the road through the south, or traverse straight through the intersection and make use of a roundabout at the *Busso-Peus Straße* to return to the intersection and make a right hand turn. These alternatives are depicted in Figure 4.2. The very few vehicles attempting to turn left into the northern *Correnssstraße* (2 vehicles in peak hour), can make use of the *Hortsmarer Landweg*, as depicted in Figure 4.3. Consequently, a slightly varied traffic flow distribution is calculated, as shown in Figure 4.4, with four major flows crossing east-west and turning between north-east.

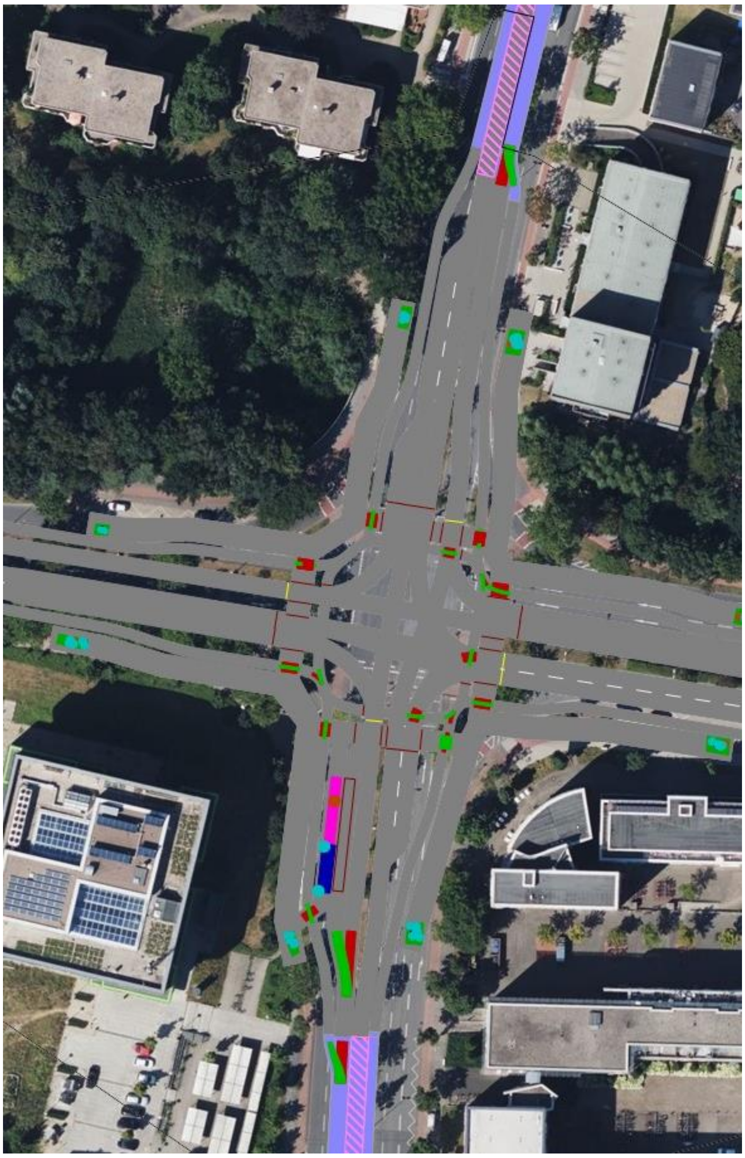

Figure 4.1: Digital model of alternative 1 in Vissim.

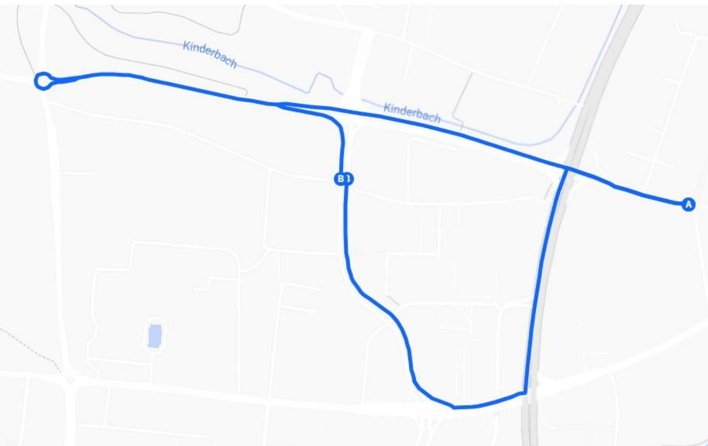

Figure 4.2: Alternative routes to southern Corrensstraße under alternative 1. Created using [38].

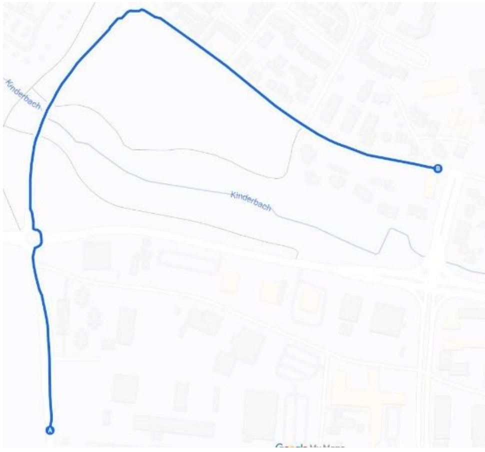

Figure 4.3: Alternative route to northern Corrensstraße under alternative 1. Created using [38].

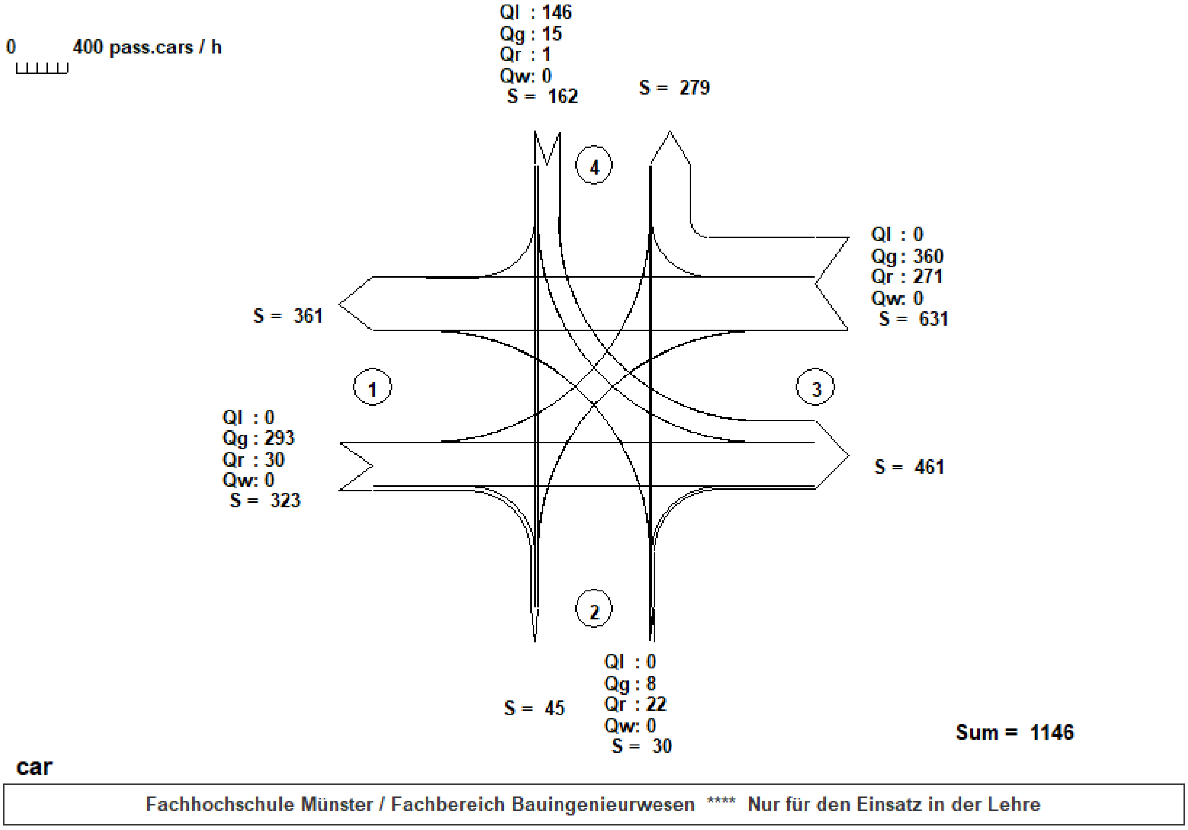

Figure 4.4: Traffic flows through alternative 1. Created using Kreisel [8].

4.2.2 Alternative 2: Small Roundabout

The second alternative is constituted of a small roundabout. Due to high traffic counts in the intersection, a segregated roundabout was chosen, wherein the bicyclists are routed around the outside of the circular lane. Following the vision of the municipality and reflecting conflicts which arise when this is not the case, bicyclists and pedestrians are given priority when crossing the motorized traffic lanes. The bus stop location is chosen to be on the primary lane of travel, as the bus will already be challenged to traverse the roundabout, and an additional swerve into a layby stop would significantly decrease the possible speed of the bus exiting the roundabout. The resulting geometric design of the intersection is shown below in Figure 4.5. For this alternative, any direction can be accessed from any direction. Therefore, the original O-D matrices can be used, the peak values of which are shown in Figure 4.6. In this figure, the asymmetrical flow through the roundabout can be seen, with the *Correnssstraße* south having the largest through traffic and lowest entering and exiting traffic. Although the eastern link has the highest traffic demand, the other two links are able to depict a smaller deviation from it than originally anticipated from Figure 2.5.

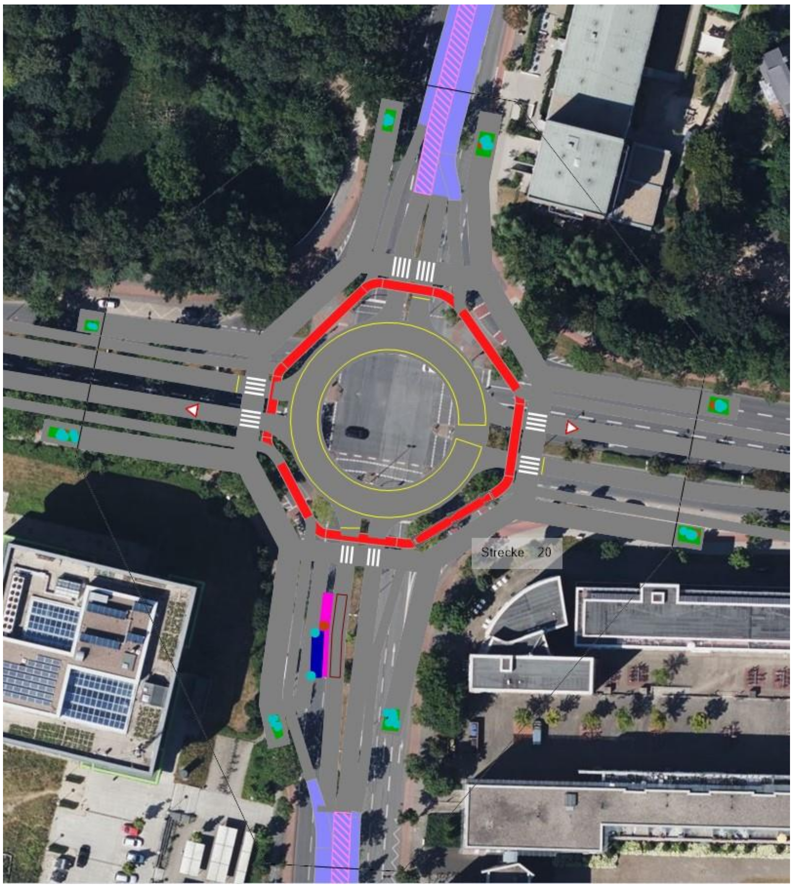

Figure 4.5: Digital model of alternative 2 in Vissim.

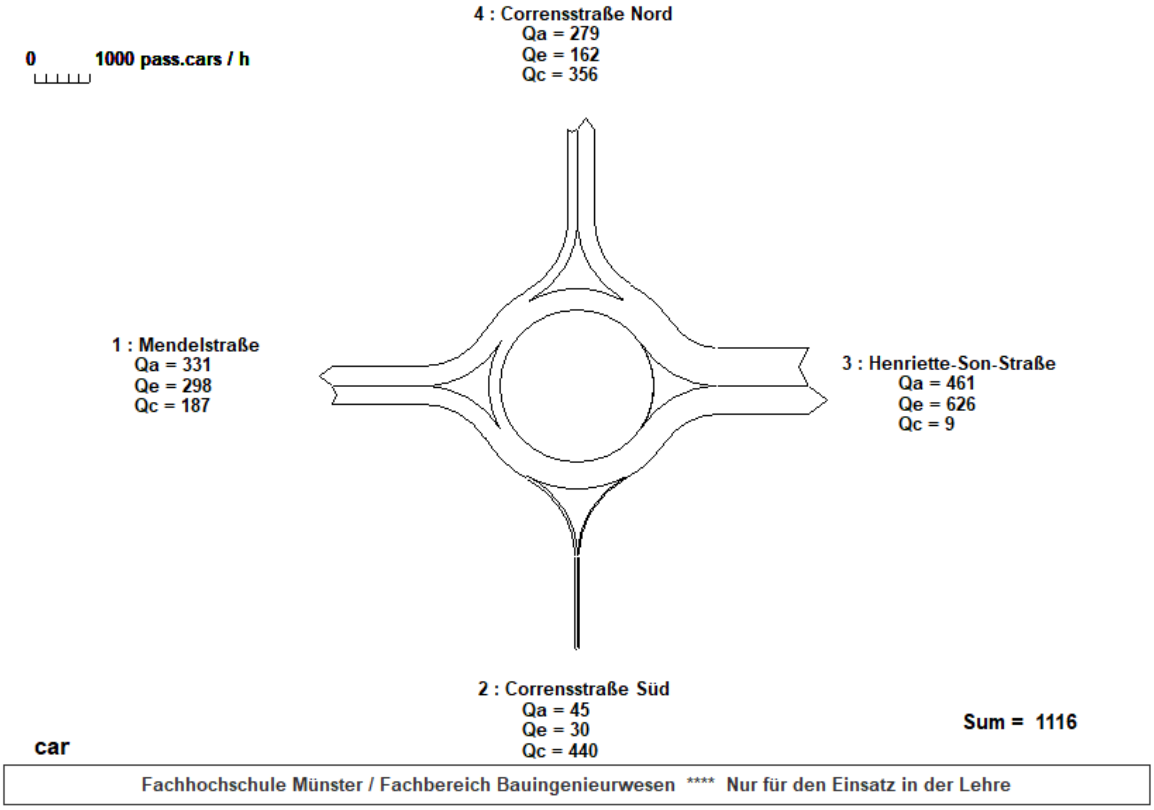

Figure 4.6: Traffic flows through alternative 2. Created using Kreisel [8].

4.2.3 Alternative 3: Severe Restrictions

The third alternative features significant interventions into the traffic flow possibilities through the intersection. Like Alternative 1, vehicles are unable to turn left from the eastern and western directions. At the same time, however, private motorists from the north and south are restricted to only turning right, with an exception made for buses in the form of a special bus lane. These restrictions are enforced by a raised median in the center of the intersection. This median can be crossed by buses and emergency vehicles to ensure infrastructural functionality. Due to the infrequency of buses, the *Corrensstraße* is treated as a priority road to facilitate a passage of pedestrians and cyclists. This does also entail, however, that bicyclists do not have priority when crossing the *Corrensstraße*. Although the east-west link crossing the intersection has the highest traffic demand, this solution should accommodate the flows better than Alternative 2, as disturbing traffic only occurs due to non-motorized vehicles and buses. The resulting design is presented below in Figure 4.7. The prevailing traffic flows are revealed by Figure 4.8, consisting primarily of traffic crossing the *Corrensstraße* and turning northwards from the east.

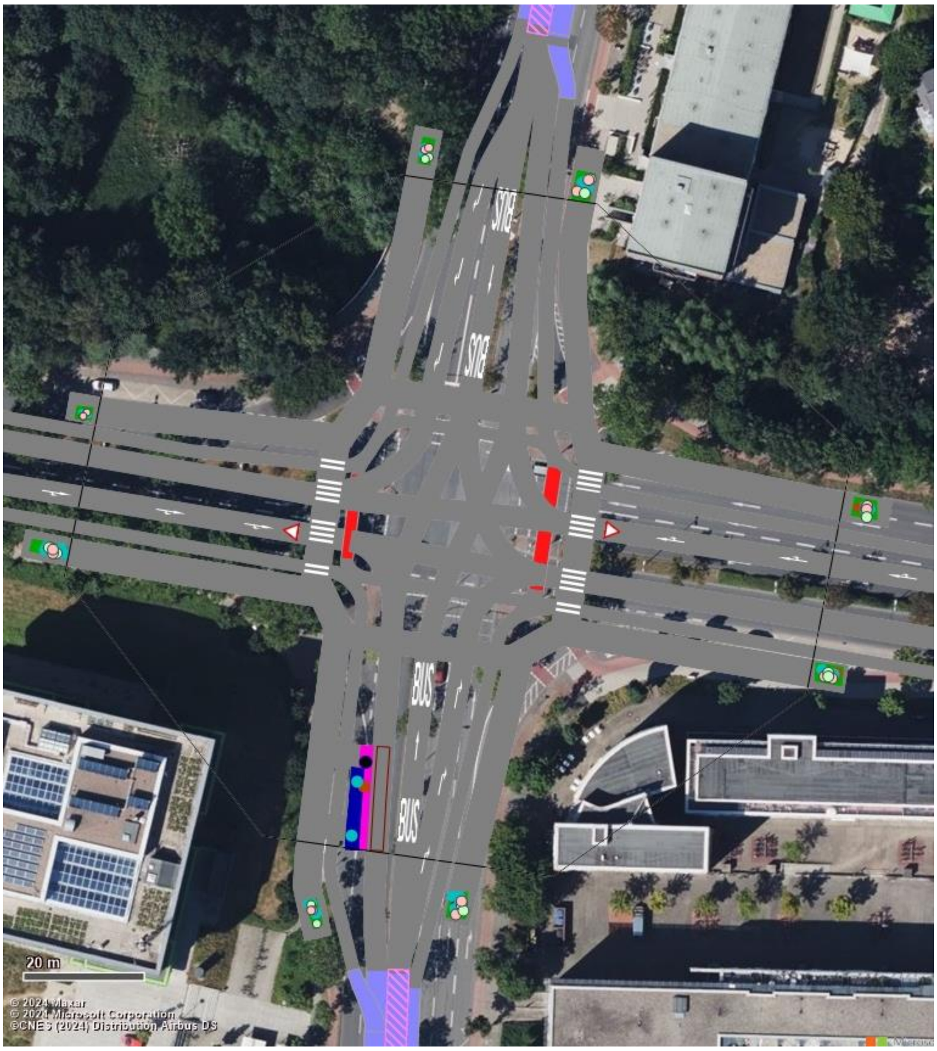

Figure 4.7: Digital model of alternative 3 in Vissim.

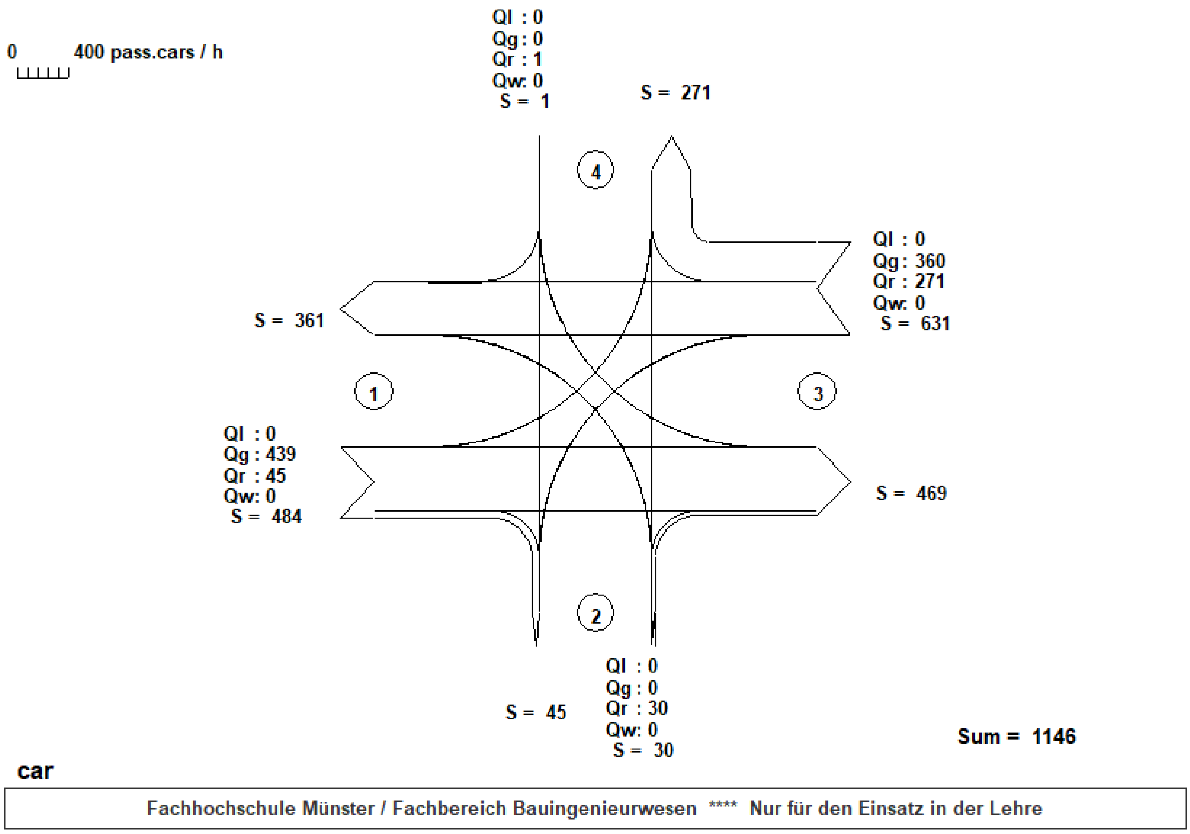

Figure 4.8: Traffic flows through alternative 3. Created using Kreisel [8].

4.2.4 Alternative 4: *Fahrradstraße*

The final alternative sees a drastic restructuring of the intersection and its surrounding road links, turning the *Corrensstraße* into a bicycle road fully crossing the intersection. Although private vehicles are allowed on such roads, bicycles have absolute priority and vehicles may only pass when it is safe to do so. Together with calming traffic and decreasing the desirability to drive along the road, the bicycle road encourages the usage of bicycles. By implementing it, a seamless connection to the velo route, or bicycle highway, passing north along the *Horstmarer Landweg* is created, providing an unsignalized connection between the university campus and Münster city center, as well as the surrounding townships. Although the implementation is likely to increase the congestion for through traffic, such a measure is probable to decrease the total through traffic, with many users incentivized to instead use the major links surrounding the area. The alternative is shown in Figure 4.9 below. The traffic flows through this intersection are identical to those of the current situation, as shown in Figure 2.7.

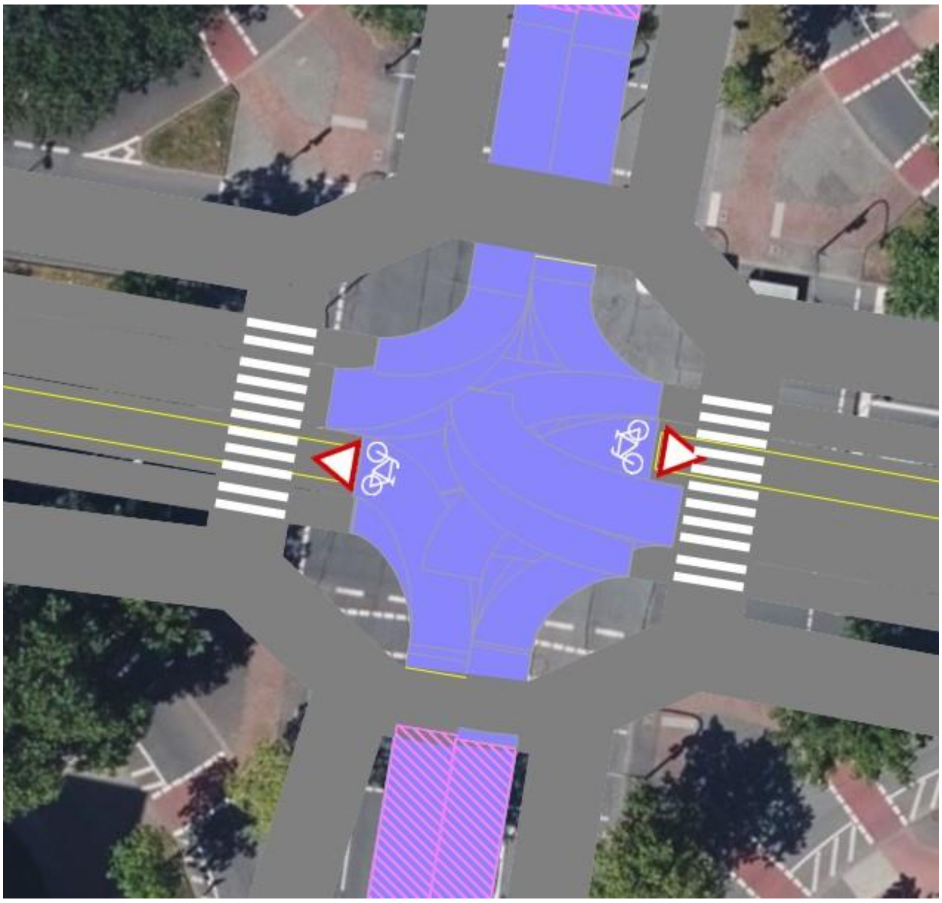

Figure 4.9: Digital model of alternative 4 in Vissim.

5. Evaluate: Performance of Alternatives

In this chapter, the performance of the different design alternatives is evaluated according to the design criteria established in Table 3.2. The methodology for measuring each indicator is first explained before the results are presented. The current situation is included as alternative 0 for comparison, however it does not fulfill the basic design requirements, wherefore it cannot be considered a viable solution. Next, some key sensitivities are explored to gain a perspective on the robustness of the initial results. Finally, as a conclusion of the results and sensitivity, a final design is drawn and a design recommendation for the municipality is given.

5.1 Method for Evaluation

To obtain objective values for each intersection design which accurately represent or approximate the performance of each alternative in light of the design criteria, each value must be calculated with a consistent method. The methods are therefore depicted in this subsection. For criteria derived from simulation runs which output a certain amount of uncertainty due to the stochastic behavior of traffic, five simulation runs are used. Running more simulations per alternative is deemed not feasible, due to time constraints and hardware constraints on data storage and processing speed. As an output, the statistical mean, median, and standard deviation are analyzed, together with the observed minimum and maximum. In this way, a more thorough comparison of alternatives can occur.

The first set of design criteria are evaluated using the SSAM software, which analyzes the traced vehicle trajectories of each entity in the Vissim simulation. It calculates the TTC and PET for any interaction within the simulation, and, being given a set of thresholds, determines whether these are conflicts or not. The thresholds used are a maximum time-to-collision of 5 seconds and a maximum post-encroachment time of 6 seconds. These values are chosen, as any values above these thresholds are determined as “common conflicts,” which allow sufficient reaction time to avoid any danger whilst maintaining control [32]. These thresholds allow for the observation of a wide range of conflicts, reaching from severe conflicts to minor decelerations. The other two SSAM measurements, ΔS and DR, are automatic outputs for conflicts which fall into the aforementioned thresholds. These two measures are therefore directly evaluated, along with the number of conflicts recorded according to the thresholds.

Next, several direct geometric criteria are considered. Firstly, the total amount of points of conflict are counted, along with their type of interaction. This constitutes the points of conflict criterion, whilst their danger is evaluated using accident statistics as a proxy for the danger of each interaction, taken from [33]. Additionally, a distinction is made between signalized and unsignalized points of conflict, as only about 0.8% of vehicles in Germany run a red light [34]. The summated danger is divided by the total amount of conflicts to produce the Conflict Danger criterion. Alongside the crash statistics, the severity and likelihood of each conflict point is estimated with the collision angle between motorized vehicles, as well as with cyclists. The angle is measured tangentially, meaning a 90-degree angle depicts a crossing traffic movement. The performance of this criterion is defined as the deviation from the optimal collision angle determined in Table 3.2. The other geometric criteria which can be directly measured are the total intersection area, the % of vegetation cover, and the % space reserved for sustainable travel.

The remaining design criteria are evaluated using direct outputs from the Vissim software. These include the CO_x emissions through the intersection, pedestrian detours, and travel times. These criteria are measured and scored according to their comparison to the current situation.

To preserve and effectively enact the weightings of the different criteria, the current situation is defined as the baseline, being given a 0 in each criterion. Following this definition, each alternative is given a score based on its percentage deviation from the current situation. This is done by dividing the score of the alternative by the total of the current situation. To then accurately assign positive and negative points, two different formulae are used. If the optimal value of the criterion is a high value, 1 is subtracted from the final ratio produced by the division above. If the criterion is defined by an optimal minimum value, the ratio itself is subtracted from 1. Thereby, the best performing alternative will always obtain the highest point for its performance, whilst remaining relative to the scaled improvement it makes compared to the current situation. Following the determination of each alternative's points, they are multiplied by the weightings of the criteria to obtain final scorings for each criteria group. The performance within each group is then multiplied by the weighting of this group itself. The reasoning for this staggered weighting of the criteria is twofold. For one, the quantity of criteria within a criteria grouping are nullified, preventing a factor such as delays from becoming more significant due to them being measured every hour rather than aggregated for an entire day. At the same time, this method allows for intermediate results to be viewed transparently, providing more thorough insight into the respective performances, strengths, and weaknesses of each alternative.

5.2 Performance of Design Alternatives

Each model was run for five simulated days, wherein the seed number between the different alternatives remained constant to ensure identical traffic counts and temporal distributions. The results of each alternative are presented below in Table 5.1, together with their summated score according to the criteria weightings and method of normalization. The complete values and resulting points for each alternative are presented in the Appendix in Table 9.6 and Table 9.7.

Table 5.1: Final aggregated scores of the design alternatives.

Criteria	Alt0	Alt1	Alt2	Alt3	Alt4
Safety	0.0	6.1	-2.2	-7.5	-9.7
Environment	0.0	0.7	6.4	5.5	2.1
Sustainable Travel	0.0	-6.3	2.8	4.9	3.4
Accessibility	0.0	-7.3	-0.1	-2.2	-9.3
Unweighted Total	0.0	-6.8	6.9	0.7	-13.5
Weighted Total	0.0	6.5	39.2	-11.4	-83.2

From the aggregated results, it is visible that certain design alternatives perform favorably in separate criteria groupings, as well as receiving significantly low results in others. The origin of these deviations is essential to understand to minimize unwanted anomalies and outliers from dominating the final decision-making process. Therefore, the characteristics of major decisive criteria are investigated to ensure that the averages made use of are representative of the performance of each alternative.

Several highly influential criteria lie within the environmental category, as it is comprised of only three indicators and carries an overall weighting of seven. Within this category, the total area of the intersection is decreased similarly by alternatives one through three, with four significantly reducing the total area. Therefore, the scoring received varies little, with alternative four gaining points for reducing the blueprint of the intersection by an additional 2 500 m^2. The criterion which has the largest influence within the environmental grouping, however, is the vegetation cover. This is because only two of the drafted designs feature a significant portion of open greenspace due to their segregated design. These alternatives are two and three, gaining 2.7 and 3.7 points, respectively. Finally, the CO_X emissions of vehicles traversing the intersection also causes a difference in scoring. The emissions observed within the digital model is calculated using a standard emissions model implemented directly within Vissim, which considers the time spent within the intersection, as well as the total acceleration required throughout the intersection. Therefore, the measure can also be used as a proxy for the overall traffic flow in each alternative. As both alternative two and three feature designs which may increase travel times but aim at decreasing stoppages in traffic, the results obtained from this measurement appear plausible.

The most influential category of criteria is user safety. Various measures are used as a proxy to obtain an objective safety rating of each intersection. Certain criteria are favored by a type of design alternative. For example, the number of conflicts is likely to decrease drastically in signalized intersections, as dangerous situations are only possible when traffic rules are ignored. However, the degree of danger of each conflict experienced is likely to increase, as a vehicle running a red light is less to be expected than one ignoring priority rules. This notion is supported by the distributions of the

TTC and PET criteria per alternative. These distributions are shown below in Figure 5.1 and Figure 5.2. It is therein visible that alternative one faces a severe increase in danger of collision, and alternative four a slight increase. The other two design alternatives show an increased TTC and PET, allowing drivers more time to react to conflicts. At the same time, all four alternatives face a shift towards higher ΔS, as shown in Figure 5.3, most likely due to the implementation of priority rulings over signalized traffic. This notion is supported by alternative one being least affected by a distribution favoring a higher difference in speeds. Finally, the conflict danger criterion severely affects all the design alternatives. Alternative one benefits within this criterion, as drivers crossing points of conflict must not pay attention to many other users to safely traverse the intersection. Users in the other alternatives often must pay attention to a variety of simultaneous traffic flows, especially in alternative three which may be counter-intuitive for many drivers.

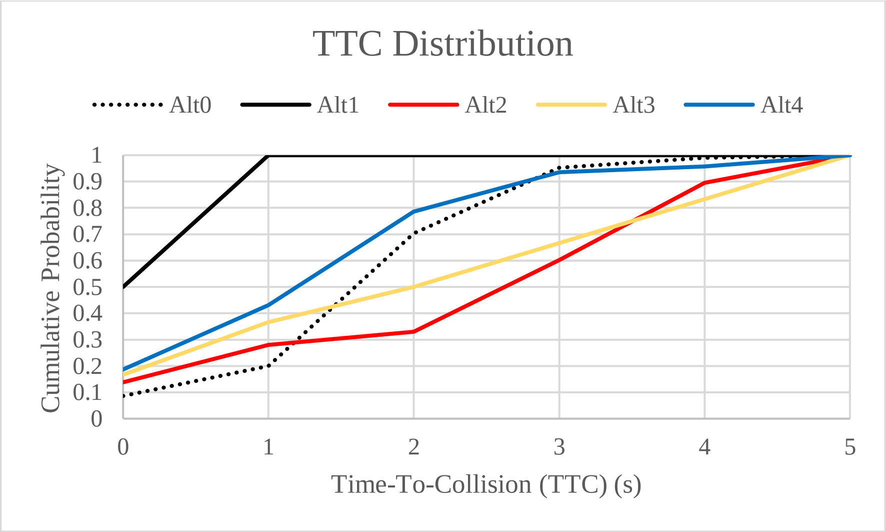

Figure 5.1: Cumulative Time-To-Collision distribution per alternative.

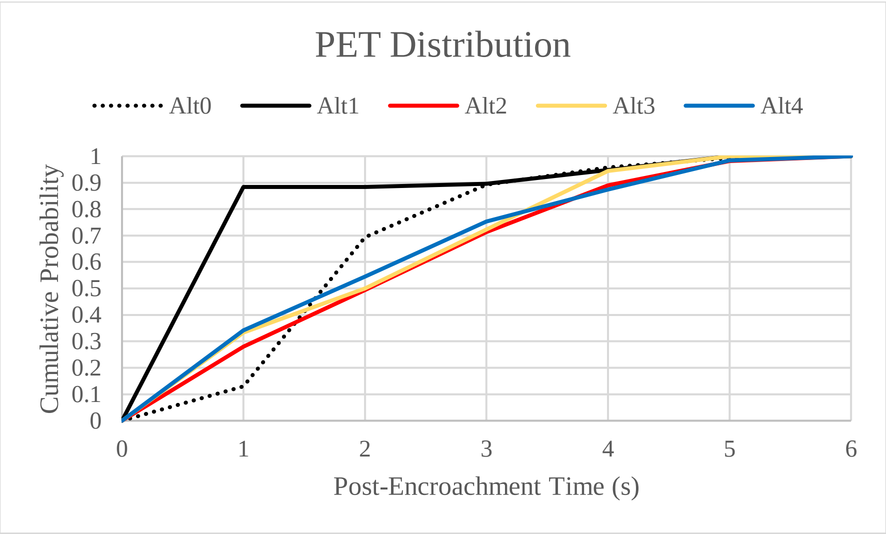

Figure 5.2: Cumulative Post-Encroachment Time distribution per alternative.

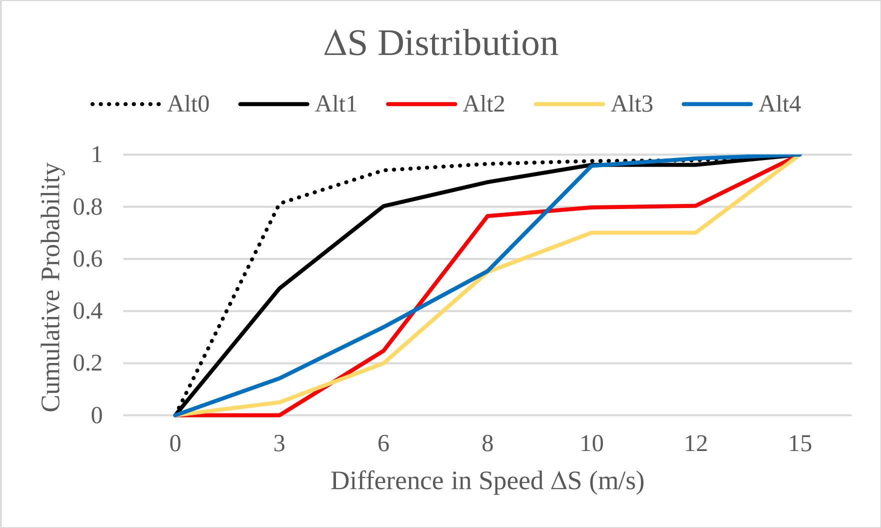

Figure 5.3: Cumulative ΔS distribution per alternative.

Reflecting the surrounding developments, the intersection should also sufficiently incorporate sustainable travel choices. Therefore, the cyclist times, pedestrian detours and travel times, and bus delays are considered important aspects of each design alternative. Pedestrian travel times and detours remain unaffected across all design alternatives, with cyclist times decreasing for all but alternative one, due to shorter effective green times. For the same reason, alternative one incurs an increase in bus delays, with the other alternatives significantly reducing the travel time for public transportation.

The accessibility criteria group ensures that the intersection designs continue to function as an integral part of the road infrastructure in Münster. Vehicle travel times can, within reason, be increased by the intersection. Vehicle queues can also be accepted during the peak hours, however a significant queue reaching into other neighboring intersections is undesirable. Therefore, the overall travel times have small effect on the scoring of alternatives, whilst the maximum queue is highly influential. Particularly alternatives one and four are negatively affected, with queue lengths of 271 and 345 meters, respectively causing -6.4 and -9.0 points per alternative. This drastic result remains within reason, however, as the other two design alternatives manage to maintain maximum queues to lengths similar to the current situation.

It can therefore be concluded that, according to the determined design criteria, the most suitable design for the intersection is a segregated roundabout.

5.3 Sensitivity Analysis

Prior to the final determination of a design recommendation, the robustness of the initial results is investigated. Apart from potential inconsistencies in the evaluation of raw results investigated in the previous section, the traffic models themselves, as well as inputs to SSAM may have a profound effect on the results. It is therefore important to establish the effects of certain input variables on the produced outputs. In addition to evaluating the quality of the obtained results, this analysis also creates a perspective on the potential performances of the alternatives under certain conditions, such as a potential increase in traffic on certain days. A sensitivity analysis is therefore conducted for the pedestrian demand, total traffic demands, and the threshold conflict angle in SSAM.

A variable for which there is no data to calibrate the models to is the pedestrian travel demand. Therefore, the sensitivity of the different alternatives' results to this variable is tested. To do so, a single simulation run is done with a 50% reduction, a 25% reduction, a 25% increase, and a 50% increase in pedestrian travel demand. With the full results presented in 9.5.1, it can be concluded that the pedestrian demand does not have a decisive effect on the daily conflict count, nor bus delays. However, an influence on emissions is visible. This is likely due to the increased stoppages with more pedestrian activity at the intersection.

Secondly, the sensitivity of the models is tested against the total traffic demand. Due to the method using which the models were built, this demand encompasses the motorized and bicycle traffic in the intersection, without a simple possibility to separate the two variables. Therefore, to remain within a reasonable range, the models are tested for a 10% and 20% decrease and increase, respectively. The resulting sensitivities reveal patterns of the different alternatives. Alternative one proves to be the most sensitive to increases in traffic demand in all three variables. Similarly, alternative three shows an increase in bus delay and total conflict count given an increase in traffic demand. The only output which is affected by the traffic demand in alternative four are emissions, most likely due to increased stoppages along the *Henriette-Son Straße*, whilst alternative two proves insensitive in these areas, with a slight increase in total conflicts with a 20% increase in traffic demand. The detailed results can be found in Appendix 9.5.2.

The final sensitivity analyzed regards the threshold conflict angle. The angle used for the main analysis is 80°, with an increase in the angle resulting in a decrease in conflicts. As the threshold angle is used within the SSAM software and not Vissim, the sensitivity is analyzed in regards to only the amount of conflicts, with additional graphs included to portray a potential change in the distribution of the danger of the conflicts, shown in Appendix 9.5.3. The sensitivity to the total amount of conflicts is shown below in Figure 5.4.

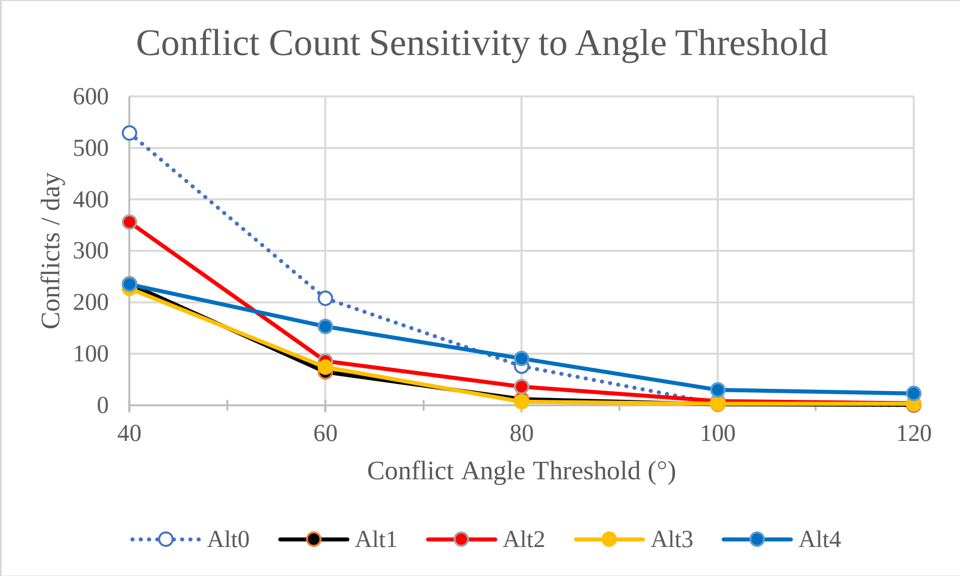

Figure 5.4: Conflict count sensitivity to conflict angle threshold per alternative.

As visible in the figure, all design alternatives are less sensitive to the threshold value than the current situation. This is most likely due to the right-turn slip lanes currently in place, where bicyclists meet cars at a tight angle between 80 and 40 degrees. Using the distributions presented in Appendix 9.5.3, certain inferences can also be made about the safety of the different sensitivities shown above.

In the current situation, the TTC and PET indicators are distributed in a safer manner provided a wider range of angles is taken into account. This indicates that the majority of more dangerous conflicts occurs at a larger angle, and most are perpendicular. This can often indicate that they may be easier to avoid, especially given the sensitivity of the required deceleration rate showing that they are only slightly more severe conflicts than at smaller angles.

The simulation runs for alternative one yielded mostly direct collisions as conflicts. With a decrease in angle of collision, more conflicts arise which do not include collisions. This decreased danger with a decreased angle is reflected by the difference in speed and required deceleration distributions. Nevertheless, the high quantity of collisions can only be traced back to a simulation error, as such distributions could not be identified during any of the other simulations of alternative one.

Alternative two follows a similar trend to the previous two models, with an increased threshold angle leading to more severe collisions. In this case, however, a decrease in angle does not drastically deviate from the original 80-degree angle used in the evaluation. Additionally, the statistics for conflicts with large angles are sensitive, due to an exceptionally low number of angles between users exceeding 90 degrees in the roundabout design alternative.

The results of the third design alternative's sensitivity differ from the previous designs, with an increase in threshold angle leading to safer values for all proxy indicators except the difference in speed. These values are, however, similarly to alternative two sensitive due to the small number of total conflicts.

The fourth design alternative reflects the patterns of the other alternatives, with a decrease in the threshold angle also leading to an improvement of the proxy indicators. Merely the deceleration rate shows a slight increase due to the decreased threshold angle. An increased threshold angle produces drastically decreased TTC and PET statistics, indicating more severe collision probabilities. However, these values coincide with a decreased difference in speed, suggesting they may be the result of including more conflicts between cyclists or cyclists and pedestrians.

5.4 Final Design Recommendations

Concluding from the analysis, alternative two is shown as the best performing option investigated. This notion is supported by the sensitivity analysis above, with alternative two proving least sensitive to varying inputs. Hence, this insensitivity proves that a roundabout is able to service the design criteria in a wide range of scenarios which may arise due to the uncertainty of the future situation. However, it is not optimal, with a decreased safety score in comparison to the current situation. In this section, these drawbacks are investigated, and a consequent final design recommendation is given, featuring elements which are aimed at mitigating these drawbacks.

The most severe deficit of alternative two lies in the criterion ΔS, with an average conflict speed difference of 8.39 ms^{-1} or 30 kmh^{-1}. Such a difference in speed suggests a conflict between motorized vehicles and pedestrians or cyclists. To reduce this factor, implementing measures aimed at reducing car speed at the conflict points is essential. A measure introduced in the final design recommendation is therefore the addition of a raised pedestrian crossing. Numerous positive effects are to be expected from such an implementation, including the reduction of car speed independent of whether pedestrians are crossing or not, and an increase of vehicle yield rate to pedestrians [27]. Although such an implementation is likely to slightly decrease the capacity of an intersection due to forcing drivers to slow down, this effect is assumed to be negligible, as vehicles must traverse the roundabout with reduced speed, nonetheless. Due to potential discomfort to passengers along the bus line, the recommendation is to install such raised crossings along two of the four links, namely the eastern and western approaches to the intersection. The implementation in the north is also unlikely to be necessary, as this road is a bicycle road and therefore drivers arrive at the intersection with an already reduced speed. This measure alone is likely to decrease the speed of drivers at the points of conflict by 12.4 kmh^{-1}, down to 17.8 kmh^{-1} [27]. Although this speed remains larger than in the current situation, it is a significant improvement, and further infringement upon vehicles may lead to an increase in queues.

To alternatively improve the safety of non-motorized users, a red-painted cycle way around the roundabout is implemented. Although results regarding the improvement regarding safety are mixed, the red-painted network functions as a clear denotation between the route of cyclists and all other users [30]. This way, conflicts between pedestrians and cyclists are less likely to occur, and motorists are reminded of the presence of the cycling path [30].

Additional modifications to the intersection made for the final design include a widening of the pedestrian crossing of the *Henriette-Son Straße* following the *Science Boulevard* along the north-south link by one meter to a total width of four meters, as well as bicycle parking racks near the bus station. This modification was made as a consequence of personal observations throughout areas of Münster which are faced with increased activity, as is the goal for the campus area. In these zones, bicycles are often tied to trees or left on the pedestrian path near points of interest. Thereby, providing parking facilities near the bus stop allows for an orderly storage of bicycles.

The rest of the detailed intersection has been designed according to the recommended values in Table 9.3. Figure 5.5 and Figure 5.6. below present the crucial dimensions of the intersection, whilst Figure 5.7 presents the final layout.

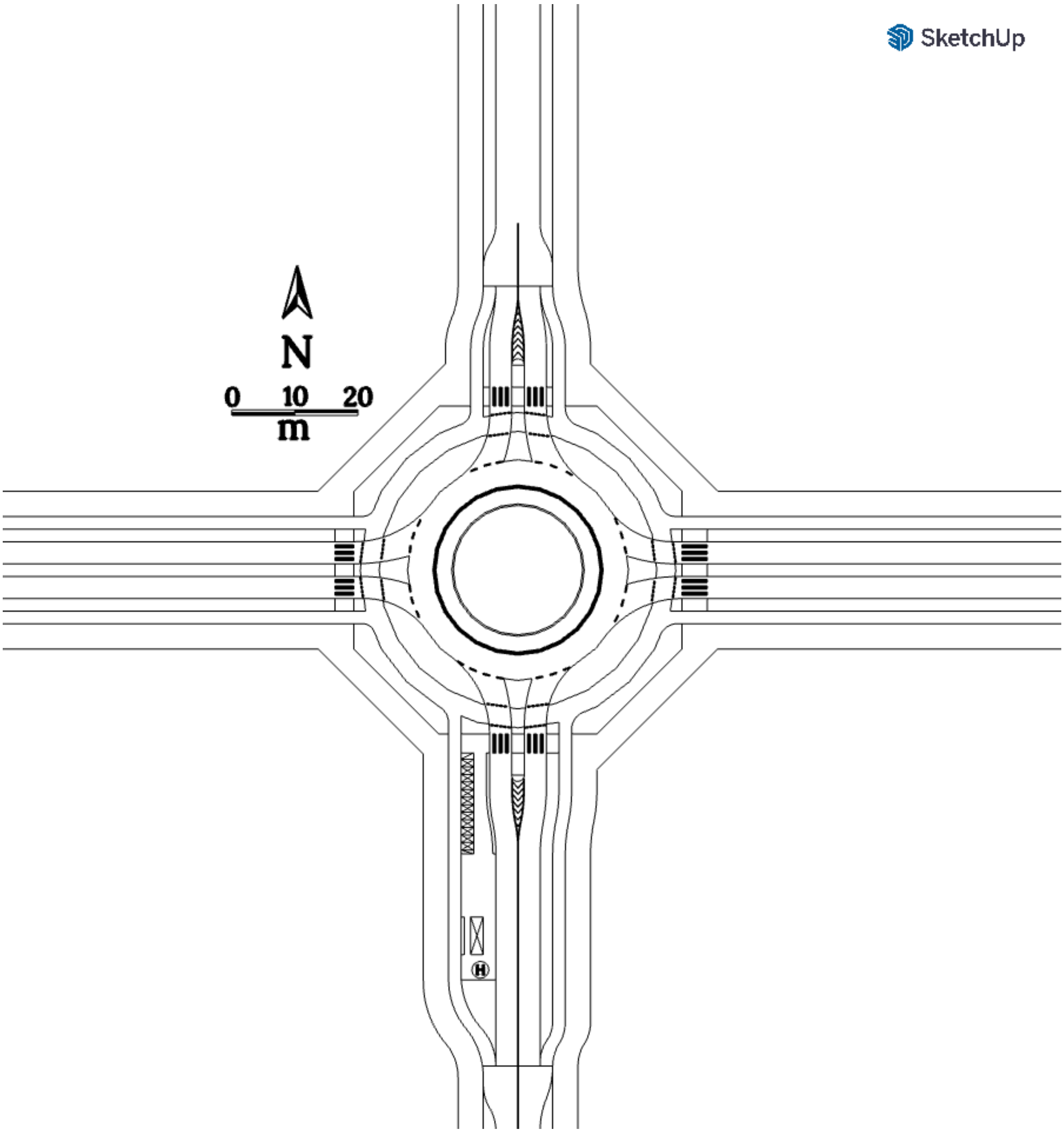

Figure 5.5: Final design recommendation schematic. Created using [35].

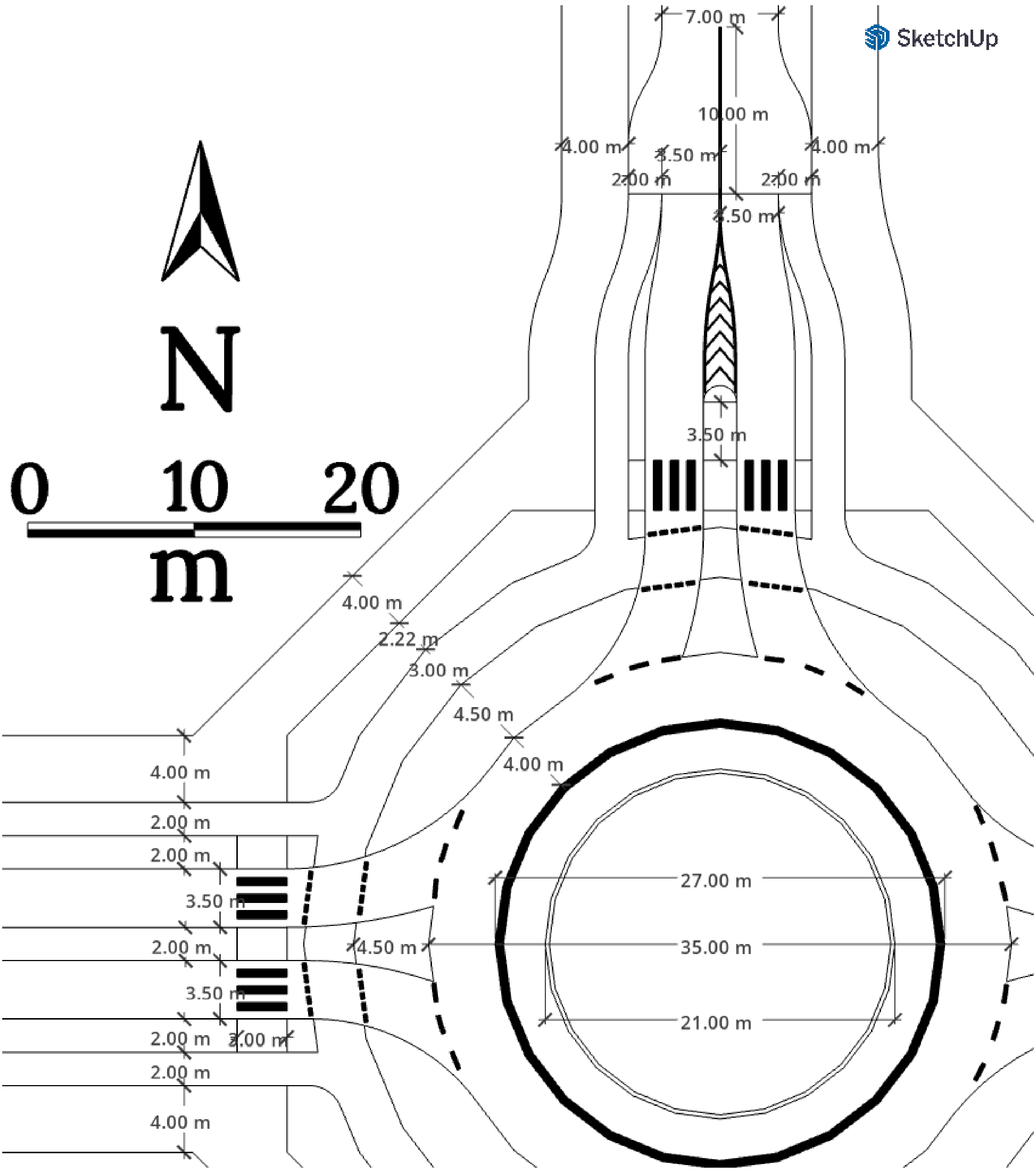

Figure 5.6: Final design dimensions. Created using [35].

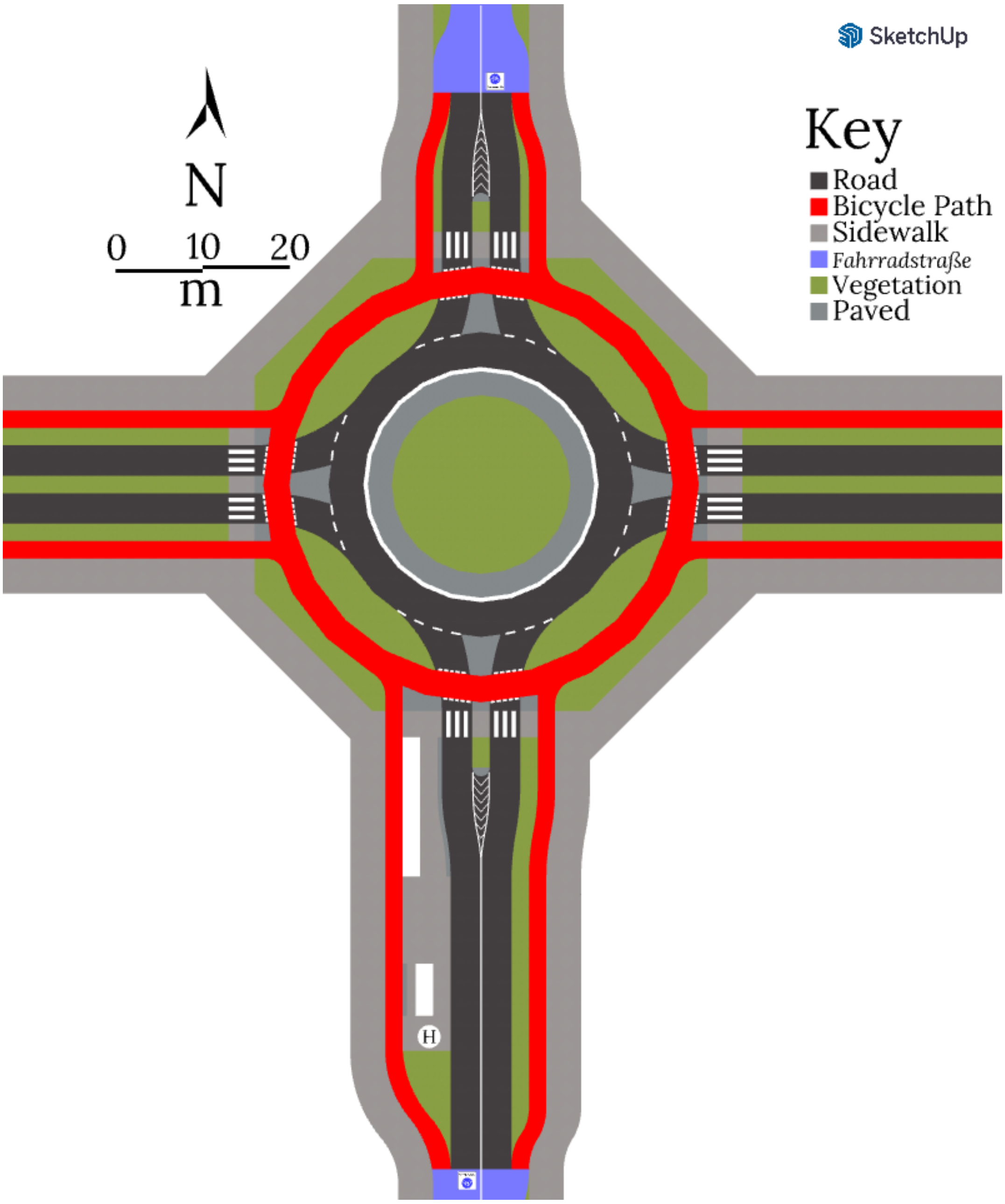

Figure 5.7: Final design recommendation. Created using [35].

Shown on the edges of the diagrams are the points of integration into the local network, where the assumption is made that there are minimal changes to the *Henriette-Son Straße/Mendelstraße*, running with a consistent vegetated median. The only modification made to this connection is a lane reduction in the *Henriette-Son Straße*, from two lanes per direction to one. The merges of the intersection to the *Correnssstraße* are different in the north and south to accommodate the bus stop directly in the vicinity of the roundabout. This allows bicycles to bypass this stop without having to wait behind a stopped bus. In all the merging locations, the road is declared a *Fahrradstraße* in its entirety before the merging of bicyclists, giving them absolute priority. To ensure that motorists can see bicyclists before they merge, the bicycle path runs parallel to the road, which is widened at this point.

Finally, the full dimensional choices made, together with their respective requirements are presented below in Table 5.2. A final outside diameter of 35 meters is chosen to accommodate the projected traffic flows and allow for the passage of large trucks and buses, whilst minimizing the area required by the intersection. Keeping the lane width at four meters is aimed at slowing down vehicles through the intersection, potentially reducing the collision speeds further. The maneuver lane width is kept at seven meters to ensure accessibility to all vehicle types within legal limits. The maneuver space is delineated from the main lane by a wide lane marker, as well as a different material on the inside. An option for such a material is cobblestone, as it is less comfortable for drivers to traverse and therefore deters cutting the roundabout.

The entrance and exit lanes' dimensions are chosen as the middle of the required ranges. These are selected to provide sufficient space for the respective vehicles, whilst also limiting the expansion of space reserved for motorized vehicles. This allows for more vegetation in the area, as well as separation between the different users for a more pleasant atmosphere. The spaces measured for vegetation allow for the planting of trees along the roads, whilst they should not be included between the road and the cycle path within the roundabout to avoid obstructing the line of sight.

The splitter islands are implemented in the north and south, whilst the median from the east and west is continued to provide a center island. They are of equal widths, each providing two meters between the motorized lanes. The islands used to split the *Corrensstraße* are additionally extended 3.50 m from the pedestrian crossing space to provide a buffer protecting pedestrians from vehicles. The bus stop zone to the south of the intersection is designed incorporating the shelters used by the municipality, as well as providing parking space for 26 bicycles.

Table 5.2: Final dimensional choices in design recommendation.

Dimension	Unit	Requirement	Recommendation	Final
Outer Diameter	m	26 - 40	30 - 35	35
Circular Lane Width	m	-	-	4
Maneuver Lane Width	m	6.50 - 9.00	7.00	7.00
Entrance Lane Width	m	3.25 - 3.75	-	3.50
Exit Lane Width	m	3.50 - 4.00	-	3.75
Entrance Lane Radius	m	10 – 14	-	12
Exit Lane Radius	m	12 – 16	-	14
Splitter Island Width	m	>1.60	-	2.00
Splitter Island Crossing Length	m	>4.00	-	7.00 / 8.00
Splitter Island Length Ped.	m	>2.00	-	3.00 / 4.00
Splitter Island Length Cyclist	m	>2.50	-	3.00

6. Discussion

The design drawn from the performed investigation is a result of a vast variety of inputs and processes which introduce certain uncertainties and limitations. Therefore, an assessment of the robustness of these inputs and processes is necessary to properly understand the significance of the results.

Model & Result Limitations

Throughout running simulations, several model limitations became apparent. For example, the model of alternative four ran into an error when simulating a 10% increase in traffic. This error, however, was not due to the number of vehicles, as a 20% increase simulation ran without issues. Instead, the conflict zones of the alternatives would occasionally lead to vehicles yielding to one another and eventually causing a gridlock standstill. This, naturally, does not reflect reality and leads to discrepancies between the simulated intersection and how it would perform. Another clear discrepancy lies in the collision occurrence, as every alternative recorded several collisions occurring per day, including the current situation. This does not correspond to reality, as collisions are exceedingly rare. However, as this is the case for all the alternatives, it does not affect the resulting comparison between alternatives but merely the values of individual alternatives.

Measurements resulting from a simulation in *PTV Vissim* aim at imitating the performance of drivers in the real world. However, a model based on computations can only approximate reality. Therefore, the observations made using the model reach certain limitations, especially when emulating the performance of the alternatives characterized by priority rulings, rather than the signalized current situation and alternative one. The significance of these limitations is reduced by including measures taken outside of the program, however it does constitute a significant portion of the data points, creating a considerable limitation to the findings.

Reliance on Limited Inputs

Some key inputs to the investigation include the traffic prognosis according to the municipality's development plans, current traffic counts, and the perspectives of stakeholders. Each of these inputs have limits to their robustness and/or their reliability. Little information is disclosed regarding the initial calculation of the prognosis. This means that it is not known how impending increases in travel delay may affect the travel demand, nor is it known what variations in traffic are to be expected on different days or in certain conditions. In the investigation, characteristics of current travel counts were used to determine the modal split and the bicycle travel demands. Apart from potential changes to these characteristics due to the developments, the characteristics are sensitive themselves, as they were only measured on a single day in 2022. Therefore, the modal split and bicycle traffic through the intersection may differ from how it is implemented in the models. Nevertheless, the sensitivity analyses prove that the results remain robust despite their uncertainties.

The perspectives of the stakeholders, on the other hand, are not reasonably feasible to obtain reliable information about within the brief time span of the thesis project. Despite this lack in time, the information of their perspectives is crucial towards the derivation of design criteria and their weightings. During the evaluation, the weightings of the criteria is found to have a significant effect on the results. For this reason, the criteria were split into sub-groups such as safety or environment. In doing so, the best alternative for each goal is determined. If it is therefore suddenly deemed that the environmental performance of the intersection gains in importance, as could be the case from a more thorough stakeholder analysis, it is quick and easy to adapt the final performance of alternatives.

Future Research

The conducted investigation leaves several starting points for future research. In this design paper, only four selected alternatives were compared to one another to determine the design recommendation. Several other options were omitted, and other potential solutions to be investigated could also include more drastic alternatives, such as a footbridge for the *Science Boulevard*. Additionally, further research into the chosen design recommendation can be conducted, investigating the optimal roundabout diameter for this intersection, or adding a lane in the roundabout, as well as the effectivity of certain measures implemented such as the raised pedestrian crossing.

An area for academic research for which there is a need arises from the results of the SSAM analysis of all alternatives, as there is currently a lack of research comparing the analyses of SSAM in combination with Vissim to real intersections' safety performances. Not only would such an analysis improve the reliability of the results gained from such a method, but also it would enable the improvement of users' safety in intersections by being able to test a range of simple to complex interventions and evaluate their effectiveness using Vissim, rather than post-implementation studies.

7. Conclusion

In pursuit of the overarching mobility vision of Münster, a new design for the intersection between the *Correnssstraße* and the *Henriette-Son Straße/ Mendelstraße* is proposed. This recommendation is achieved after having established design criteria and examined four potential alternatives in the light of these criteria via microsimulation software. The final design specifics are presented in Section 5.4 to conclude the completion of the initial research goal. Throughout the process of answering the research goal, the various research questions have been addressed and answered as follows.

Q1 Which values are relevant to the design of the intersection?

The key values of importance in this design process are extracted from the *Münster Modell Quartier* plans, together with the overarching mobility vision of Münster, as well as from the interests of certain stakeholders. The key overall values are therein the safety of users, the environmental performance of the intersection, the attention to sustainable modes of transit, and the accessibility.

Q2 What are the problems with the current state of the intersection?

A problem analysis through the perspective of the different stakeholders is conducted to identify problems in addition to those previously presented by the municipality. These issues relate primarily to the safety of the intersection, as well as the environmental performance due to its over dimensioned capacity. Depending on the severity of problems, certain issues shape the design requirements, whilst others influence the design criteria to determine more suitable solutions.

Q3: Which criteria are effective for generating and evaluating different design alternatives?

Despite several qualitative values of stakeholders, the choice is made to record only quantitative criteria, many of which can be used as a proxy for estimating the qualitative performance of the alternatives. In doing so, a standardized method for weighting the criteria and comparing them to one another is made possible.

Q4: Which intersection designs compose an inventory of possible solutions?

Several different options are deemed feasible within the scope of the project area. Alternatives range from minimal intervention by merely reducing the lane counts to drastic interventions consisting of a continued bicycle road through the intersection. Given the space of the intersection, a bridge crossing is also theoretically feasible. Many of these solutions, however, were not investigated more closely due to a preselection procedure, during which promising alternatives were selected to limit the alternatives to a signalized intersection, a roundabout, a heavily segregated intersection, and a continued bicycle road.

Q5: What is the final design recommendation?

The final design recommendation is a roundabout with a diameter of 35 meters. To improve the safety performance of the alternative, certain extra additions are beneficial, including the addition of raised pedestrian crossings which also perform as speed bumps. By conducting a sensitivity analysis of the alternatives under certain inputs, the robustness of the results is evaluated and confirmed. The reliability of the results is additionally improved by including measures which are external to PTV Vissim, decreasing the reliance of the results on a single software.

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9. Appendices

9.1 Appendix A: Traffic Counts

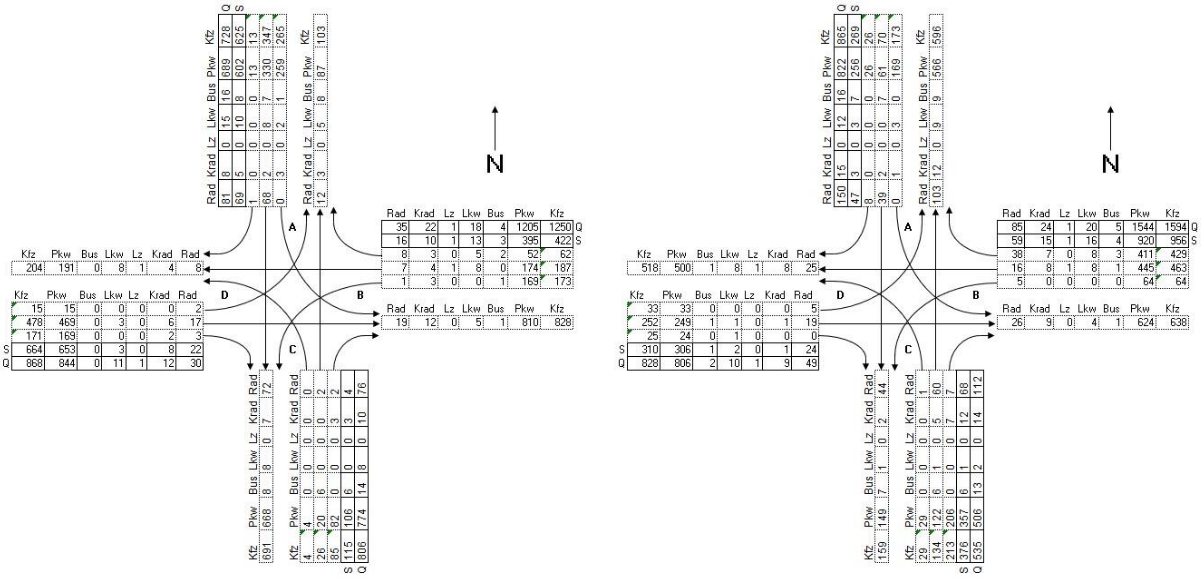


Figure 9.1: Traffic counts 2003. Left: 7.00-8.00. Right: 16.00-17.00.

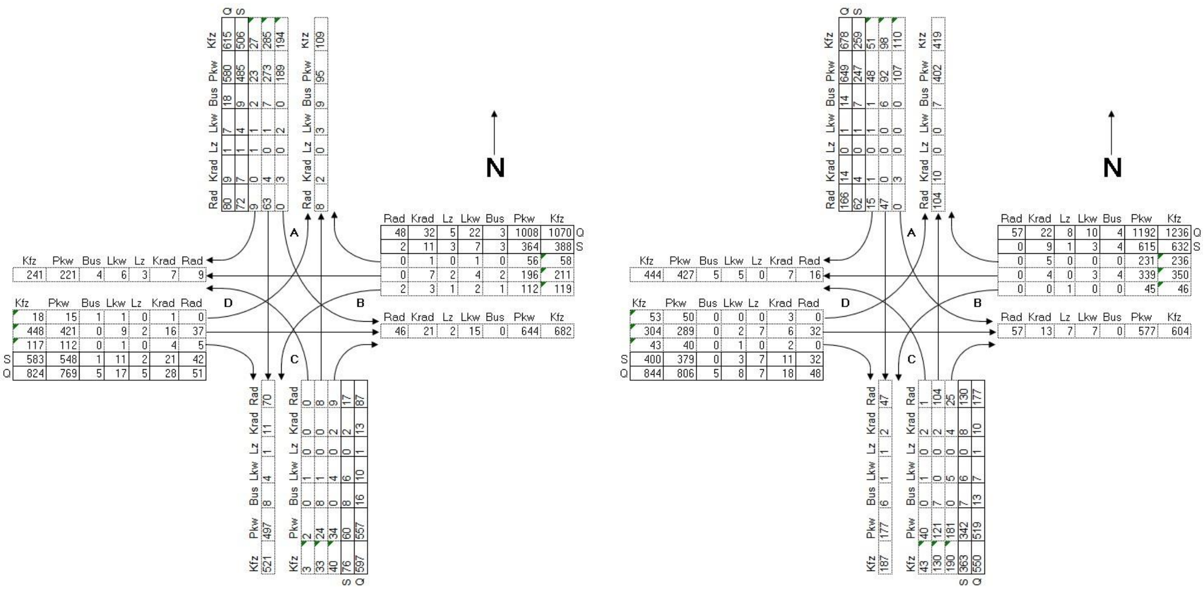


Figure 9.2: Traffic counts 2006. Left: 7.00-8.00. Right: 16.00-17.00.

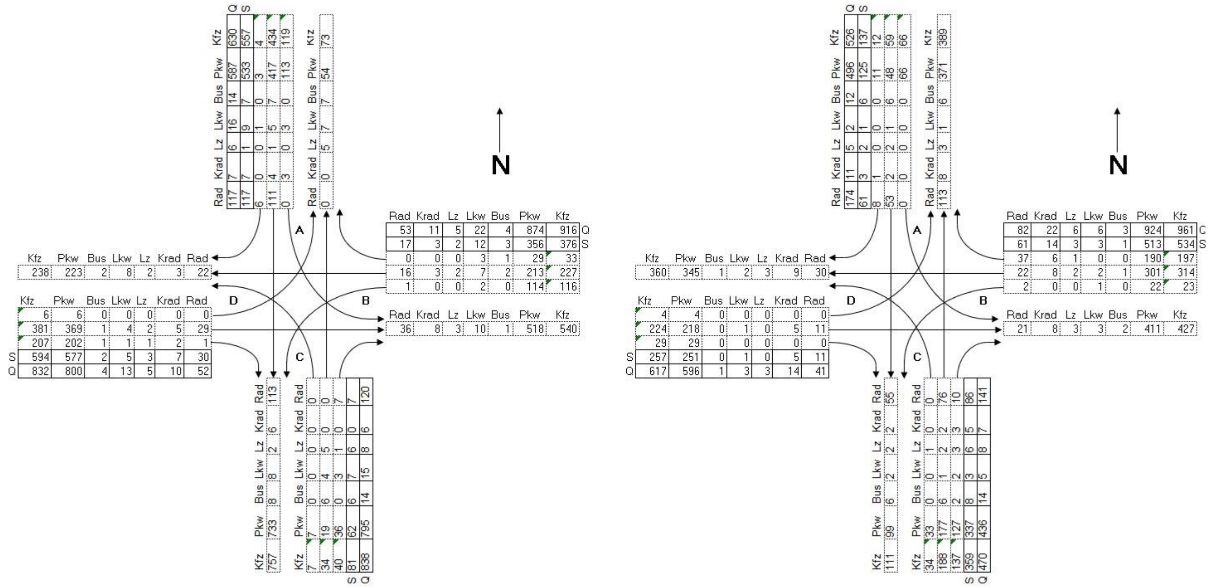


Figure 9.3: Traffic counts 2011. Left: 7.00-8.00. Right: 16.00-17.00.

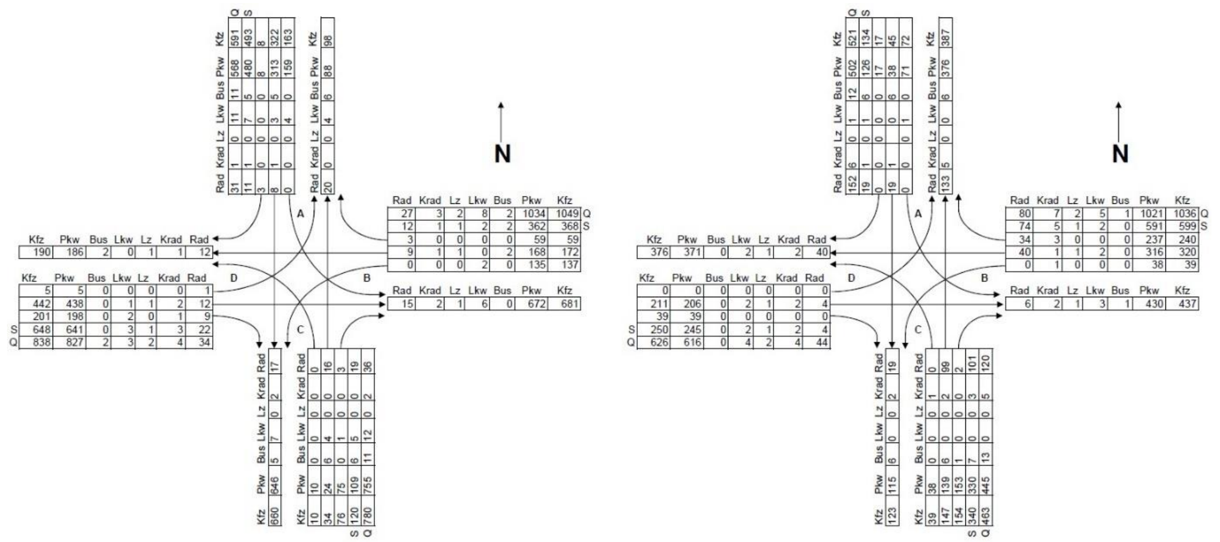


Figure 9.4: Traffic counts 2017. Left: 7.00-8.00. Right: 16.00-17.00.

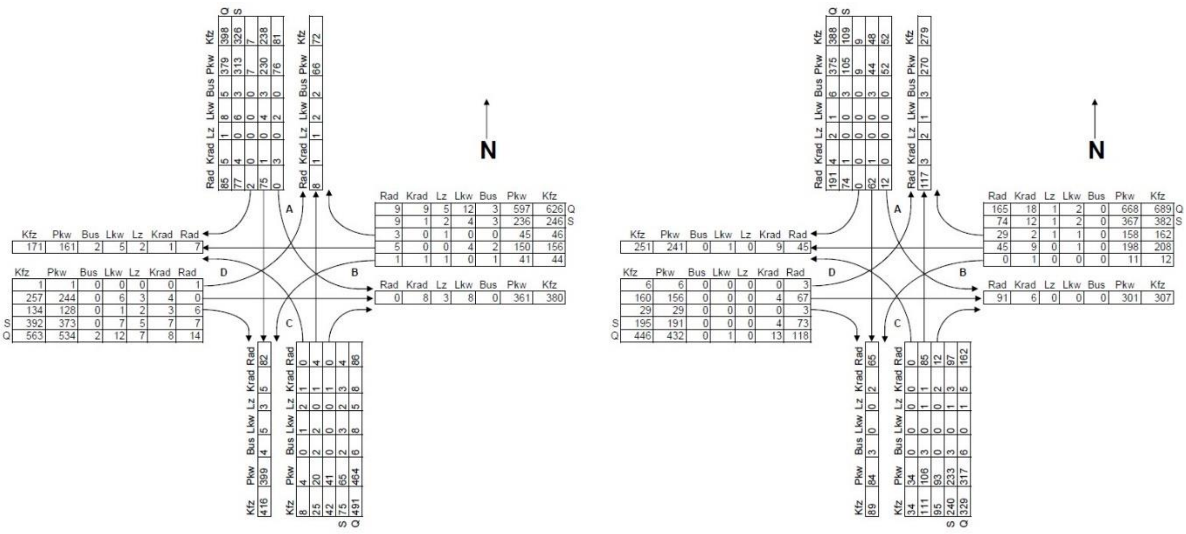


Figure 9.5: Traffic counts 2022. Left: 7.00-8.00. Right: 16.00-17.00.

9.2 Appendix B: Traffic Count Prognosis Distribution

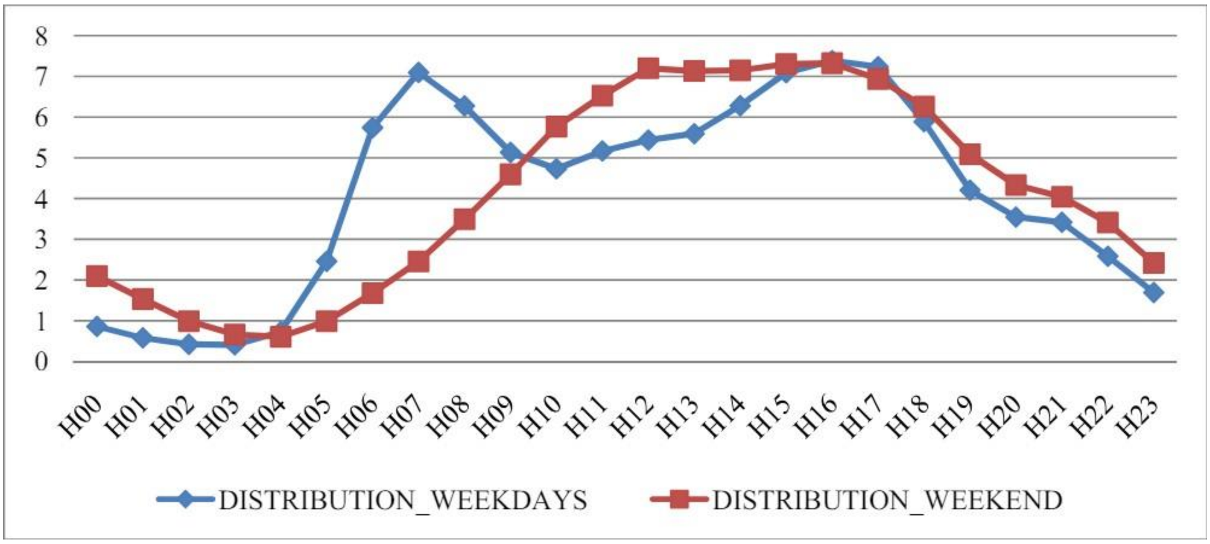


Figure 9.6: Hourly distribution of traffic in urban intersections. [6].

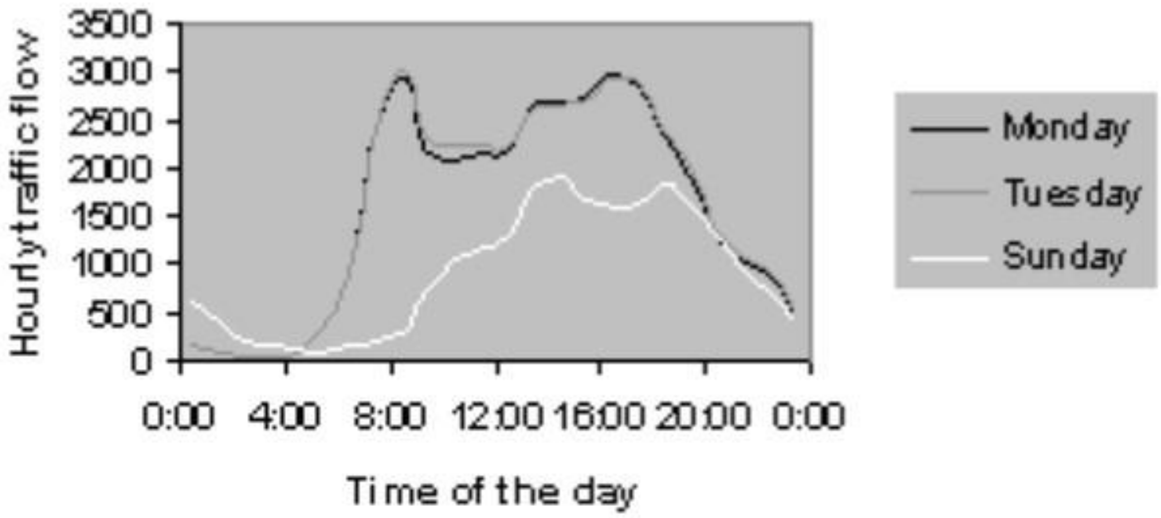


Figure 9.7: Hourly distribution of traffic in Dutch urban intersection. [7].

The table below presents the extracted ratios of each hour to the 24-hour total.

Table 9.1: Hourly distribution of traffic.

Time	Weekday [6]	Weekend [6]	Weekday [7]	Weekend [7]
0:00	0.009	0.021	0.004	0.028
1:00	0.006	0.015	0.003	0.023
2:00	0.004	0.010	0.001	0.009
3:00	0.004	0.006	0.000	0.007
4:00	0.008	0.006	0.001	0.005
5:00	0.025	0.010	0.008	0.005
6:00	0.058	0.017	0.019	0.005

7:00	0.071	0.024	0.054	0.007
8:00	0.062	0.035	0.079	0.012
9:00	0.051	0.045	0.065	0.028
10:00	0.048	0.058	0.054	0.042
11:00	0.051	0.065	0.057	0.052
12:00	0.054	0.072	0.057	0.056
13:00	0.056	0.071	0.068	0.075
14:00	0.062	0.072	0.072	0.089
15:00	0.070	0.073	0.072	0.080
16:00	0.073	0.073	0.072	0.075
17:00	0.072	0.070	0.079	0.073
18:00	0.059	0.062	0.068	0.080
19:00	0.042	0.051	0.054	0.080
20:00	0.035	0.042	0.041	0.066
21:00	0.034	0.040	0.027	0.047
22:00	0.026	0.033	0.024	0.035
23:00	0.017	0.024	0.014	0.023

Upon inspection of the two distributions, Kim et al.'s distribution fits the situation better, as the peaks align with the local traffic peaks. Additionally, the model is more recent and therefore available in higher resolution. Hence, the total 24-hour matrix presented in the report is multiplied by the factor listed in the second column of the table above to produce unique OD matrices for each hour within a weekday. For the weekend matrices, a similar process is undertaken, however the original traffic counts are multiplied by a factor of 0.75 to account for lower traffic demands on weekends [6]. The final OD-matrices are therefore presented in the table below. Due to temporal constraints, only the weekday matrices were implemented in Vissim.

Table 9.2: Final OD matrices.

Day	*Weekdays*					*Weekends*				
Time	O-D	A	B	C	D	O-D	A	B	C	D
0:00 – 1:00	A	0	18	2	0	A	0	32	3	0
	B	33	0	3	41	B	59	0	6	71
	C	1	3	0	0	C	2	5	0	0
	D	0	36	0	0	D	0	63	1	0

1:00 – 2:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	12	1	0	A	0	23	2	0
	B	22	0	2	27	B	42	0	4	51
	C	1	2	0	0	C	1	3	0	0
	D	0	24	0	0	D	0	45	1	0
2:00 – 3:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	8	1	0	A	0	15	2	0
	B	15	0	1	18	B	28	0	3	34
	C	0	1	0	0	C	1	2	0	0
	D	0	16	0	0	D	0	30	0	0
3:00 – 4:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	8	1	0	A	0	9	1	0
	B	15	0	1	18	B	17	0	2	20
	C	0	1	0	0	C	0	1	0	0
	D	0	16	0	0	D	0	18	0	0
4:00 – 5:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	16	2	0	A	0	9	1	0
	B	30	0	3	36	B	17	0	2	20
	C	1	2	0	0	C	0	1	0	0
	D	0	32	0	0	D	0	18	0	0
5:00 – 6:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	50	5	1	A	0	15	2	0
	B	93	0	9	113	B	28	0	3	34
	C	3	8	0	0	C	1	2	0	0
	D	0	100	1	0	D	0	30	0	0
6:00 – 7:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	116	12	1	A	0	26	3	0
	B	215	0	20	262	B	47	0	4	58
	C	6	17	0	1	C	1	4	0	0
	D	1	233	3	0	D	0	51	1	0
7:00 – 8:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	142	14	1	A	0	36	4	0
	B	263	0	25	320	B	67	0	6	81
	C	7	21	0	1	C	2	5	0	0
	D	1	285	4	0	D	0	72	1	0

8:00 – 9:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	124	12	1	A	0	53	5	1
	B	230	0	22	280	B	98	0	9	119
	C	6	19	0	1	C	3	8	0	0
	D	1	249	3	0	D	0	106	1	0
9:00 – 10:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	102	10	1	A	0	68	7	1
	B	189	0	18	230	B	126	0	12	153
	C	5	15	0	1	C	3	10	0	1
	D	1	205	3	0	D	1	136	2	0
10:00 – 11:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	96	10	1	A	0	87	9	1
	B	178	0	17	217	B	162	0	15	197
	C	5	14	0	1	C	4	13	0	1
	D	1	193	2	0	D	1	175	2	0
11:00 – 12:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	102	10	1	A	0	98	10	1
	B	189	0	18	230	B	181	0	17	220
	C	5	15	0	1	C	5	15	0	1
	D	1	205	3	0	D	1	196	2	0
12:00 – 13:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	108	11	1	A	0	109	11	1
	B	200	0	19	244	B	201	0	19	244
	C	5	16	0	1	C	5	16	0	1
	D	1	217	3	0	D	1	217	3	0
13:00 - 14:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	112	11	1	A	0	107	11	1
	B	208	0	20	253	B	198	0	19	241
	C	6	17	0	1	C	5	16	0	1
	D	1	225	3	0	D	1	214	3	0
14:00 – 15:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	124	12	1	A	0	109	11	1
	B	230	0	22	280	B	201	0	19	244
	C	6	19	0	1	C	5	16	0	1
	D	1	249	3	0	D	1	217	3	0

15:00 - 16:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	140	14	1	A	0	110	11	1
	B	260	0	25	316	B	204	0	19	248
	C	7	21	0	1	C	6	17	0	1
	D	1	281	4	0	D	1	220	3	0
16:00 - 17:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	146	15	1	A	0	110	11	1
	B	271	0	26	329	B	204	0	19	248
	C	7	22	0	1	C	6	17	0	1
	D	1	293	4	0	D	1	220	3	0
17:00 - 18:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	144	14	1	A	0	106	11	1
	B	267	0	25	325	B	195	0	18	237
	C	7	22	0	1	C	5	16	0	1
	D	1	289	4	0	D	1	211	3	0
18:00 – 19:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	118	12	1	A	0	93	9	1
	B	219	0	21	266	B	173	0	16	210
	C	6	18	0	1	C	5	14	0	1
	D	1	237	3	0	D	1	187	2	0
19:00 – 20:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	84	8	1	A	0	77	8	1
	B	156	0	15	190	B	142	0	13	173
	C	4	13	0	1	C	4	12	0	1
	D	1	169	2	0	D	1	154	2	0
20:00 – 21:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	70	7	1	A	0	63	6	1
	B	130	0	12	158	B	117	0	11	142
	C	4	11	0	1	C	3	9	0	1
	D	1	140	2	0	D	0	127	2	0
21:00 - 22:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	68	7	1	A	0	60	6	1
	B	126	0	12	153	B	112	0	11	136
	C	3	10	0	1	C	3	9	0	0
	D	1	136	2	0	D	0	121	2	0

	O-D	A	B	C	D	O-D	A	B	C	D
22:00 - 23:00	A	0	52	5	1	A	0	50	5	0
	B	96	0	9	117	B	92	0	9	112
	C	3	8	0	0	C	2	7	0	0
	D	0	104	1	0	D	0	99	1	0
23:00 - 24:00	O-D	A	B	C	D	O-D	A	B	C	D
	A	0	34	3	0	A	0	36	4	0
	B	63	0	6	77	B	67	0	6	81
	C	2	5	0	0	C	2	5	0	0
	D	0	68	1	0	D	0	72	1	0

9.3 Appendix C: Design Alternative Requirements

Table 9.3: Legal requirements.

Requirement	Characteristic	Value	Unit	Source
Pedestrian Requirements				EFA 2002 [36]
Network	Complete	Requirement	-	p. 9
Joined sidewalk bicycles and pedestrians				
Sidewalk 2.5-3 m wide	Maximum users	70	h^{-1}	p. 13
Sidewalk 2.5-3 m wide	Minimum pedestrians	57	%	p. 13
Sidewalk 3-4 m wide	Maximum users	100	h^{-1}	p. 13
Sidewalk 2-4m wide	Minimum pedestrians	60	%	p. 13
Sidewalk > 4 m wide	Maximum users	150	h^{-1}	p. 13
Sidewalk > 4 m wide	Minimum pedestrians	67	%	p. 13
Parking obstacles[2]	Minimum height	60	cm	p. 14
Sidewalk, road < 5000 veh/d, type 7	Minimum width	4.00	m	p. 15
Sidewalk, road < 10000 veh/d, type 6	Minimum width	4.30	m	p. 15
Sidewalk, road > 15000 veh/d, type 8	Minimum width	4.00	m	p. 15
Bus stop	Added sidewalk width	1.50	m	p. 16
Benches along sidewalk	Added sidewalk width	1.00	m	p. 16
Vegetation strip	Added sidewalk width	1.00	m	p. 16
Vegetation strip with trees	Added sidewalk width	2.00 – 2.50	m	p. 16
Bicycle parking	Added sidewalk width	2.00	m	p. 16
Angled bicycle parking	Added sidewalk width	1.50	m	p. 16
Within 200 m of kindergarten	Minimum **must** be met	Requirement	-	p. 17
Within 200 m of bus stop	Minimum **must** be met	Requirement	-	p. 17
Within 400 m of university	Minimum **must** be met	Requirement	-	p. 17
Height difference between sidewalk and street at crossing	Maximum	3	cm	p. 18
No requirement for pedestrian crossing; 2 lanes	Maximum speed limit	< 25	km/h	p. 19
No requirement for pedestrian crossing; 2 lanes	Maximum speed limit Maximum traffic	30 500	km/h veh/h	p. 19
No requirement for pedestrian crossing; 2 lanes	Maximum speed limit Maximum traffic	50 250	km/h veh/h	p. 19
Required crossing; 2 lanes	Type of crossing	Figure 9.8	-	p. 19
Required crossing; >2 lanes	Type of crossing	Signaled	-	p. 20
Required sight distance car-pedestrian; 50 km/h limit	Minimum	35	m	p. 20
Required sight distance car-pedestrian; 30 km/h limit	Minimum	15	m	p. 20
Required sight distance pedestrian-car; 50 km/h limit	Minimum	50	m	p. 20
Required sight distance pedestrian-car; 30 km/h limit	Minimum	30	m	p. 20
Crossing identification distance; 50 km/h limit	Minimum	100	m	p. 36

[2] Obstacles such as plant boxes or bicycle parking which physically prevent cars from parking alongside the road.

Crossing identification distance; 30 km/h limit	Minimum	50	m	p. 36
Width of pedestrian refuge island	Range	2.50 – 3.00	m	p. 21
Traffic light offset	Range	1 – 2	sec	p. 24
Crossing in roundabout	Maximum distance to circular lane	4	m	p. 26
Lighting requirements	All users must be well-lit	DIN 5044 DIN 67523	-	p. 30 f.
Sidewalk drainage gradient	Maximum	2.5	%	p. 32
Sidewalk crossing gradient	Maximum	6	%	p. 32
Unsignalized crossing	Range	Figure 9.9	-	p. 37
Road Requirements				RASt 2006 [37]
Heavy vehicle width	Maximum	2.55	m	p. 27
Movement width	Recommended	0.25	m	p. 25
Restricted movement width	Minimum	0.20	m	p. 25
Safety width between vehicles	Required	0.25	m	p. 25
Safety width between buses	Recommended	0.40	m	p. 25
Safety width between cyclists	Recommended	0.75	m	p. 25
Outside safety width	Minimum	0.50	m	p. 25
Restricted outside safety width	Minimum	0.25	m	p. 25
Vertical safety width	Required	0.30	m	p. 25
Heavy vehicle height	Maximum	4.50	m	p. 27
Bicycle vehicle width	Required	1.00	m	p. 27
Cargo bicycle vehicle width	Required	1.30	m	p. 28
Cycle safety from road	Minimum	0.50	m	p. 28
Cycle safety from parallel park	Minimum	0.75	m	p. 28
Cycle safety from angled park	Minimum	0.25	m	p. 28
Cycle safety from pedestrians	Minimum	0.25	m	p. 28
Disabled pedestrian width	Minimum	1.20	m	p. 29
Disabled pedestrian curve	Minimum	2.30 x 2.30	m	p. 29
Cycle distance to trees	Minimum	0.75	m	p. 30
Vehicle distance to trees	Minimum	1.00	m	p. 30
Lighting distance to trees	Minimum	3.00	m	p. 30
Road drainage angle	Required	2.5	%	p. 31
Separated lane width	Range	3.00 – 3.50	m	p. 70
Separated lane width with bus	Minimum	3.25	m	p. 70
Two-lane separated lane width	Recommended	6.50	m	p. 70
Two-lane separated lane width	Minimum	6.00	m	p. 70
Two-lane regular road width	Recommended	6.50	m	p. 69
Curb height four lane road	Range	10 – 14	cm	p. 75
Curb height four lane road	Maximum	20	cm	p. 75
Curb height two lane road	Range	8 – 12	cm	p. 75
Middle curb height	Range	4 – 6	cm	p. 75
Low curb height	Range	0 – 4	cm	p. 75
Curve radius	Minimum	10	m	p. 76
Parallel gradient	Maximum	8	%	p. 76
Perpendicular gradient	Maximum	2.5	%	p. 76
Bike lane width along road	Minimum	1.60	m	p. 84
Bike lane separation width	Minimum	0.25	m	p. 84
Bike lane distance to park lane	Minimum	0.75	m	p. 84
Separated bike lane width	Recommended	2.00	m	p. 84

Separated bike lane width	Minimum	1.60	m	p. 84
Two-way bike lane width	Recommended	2.50	m	p. 84
Two-way bike lane width	Minimum	2.00	m	p. 84
Distance between bicycle stands	Recommended	1.20	m	p. 87
Dimensions crossing signaling	Minimum	Figure 9.10	-	p. 91
Bus stop length	Minimum	Bus + 20	m	p. 102
Bus stop lane width	Minimum	3.50	m	p. 102
Raised lane height	Range	0.08 – 0.010	m	p. 108
Raised lane gradient	Recommended	1:15	m/m	p. 108
Left turn lane length	Recommended	20.00	m	p. 111
Left turn lane length	Minimum	10.00	m	p. 111
Left turn lane width	Minimum	3.00	m	p. 111
Left turn lane width	Maximum	5.50	m	p. 111
Left turn lane width to normal	Minimum	0.25 less	m	p. 111
Roundabouts				
Outside diameter	Minimum	26	m	p. 115
Outside diameter	Recommended	30 – 35	m	p. 115
Outside diameter	Maximum	40	m	p. 115
Width of circular lane Diameter; 26 m 30 m 35 m 40 m	Recommended	 9.00 8.00 7.00 6.50	 m m m m	p. 115
Perpendicular road angle	Required	2.5	%	p. 115
Curb height	Required range	0.04 – 0.05	m	p. 115
Entrance lane width	Required range	3.25 – 3.75	m	p. 116
Exit lane width	Required range	3.50 – 4.00	m	p. 116
Entrance lane radius	Required range	10 – 14	m	p. 116
Exit lane radius	Required range	12 – 16	m	p. 116
Splitter island width	Minimum	1.60	m	p. 116
Splitter island crossing width	Minimum	4.00	m	p. 116
Splitter island depth pedestrian	Minimum	2.00	m	p. 116
Splitter island depth bicyclist	Minimum	2.50	m	p. 116
Inside ring radius	Recommended	2 * lane width	m	p. 116
Traffic Signals				RiLSA 2015 [31]
Clearance time (yellow)	Recommended	3	s	p. 21
Transition signal (red, yellow)	Recommended	1	s	p. 21
Bicycle clearance time	Recommended	2	s	p. 21
Bicycle transition signal	Recommended	1	s	p. 21
Full-red transition period	Calculated in model	4	s	p. 22 - 26
Bicycle full-red transition	Calculated in model	6	s	p. 25
Pedestrian full-red transition	Calculated in model	7	s	p. 25
Effective green time per link	Calculated below	Table	%	p. 27
Effective green time per link	Minimum	5	s	p. 28
Pedestrian effective green time	Minimum	Link width	s	p. 28

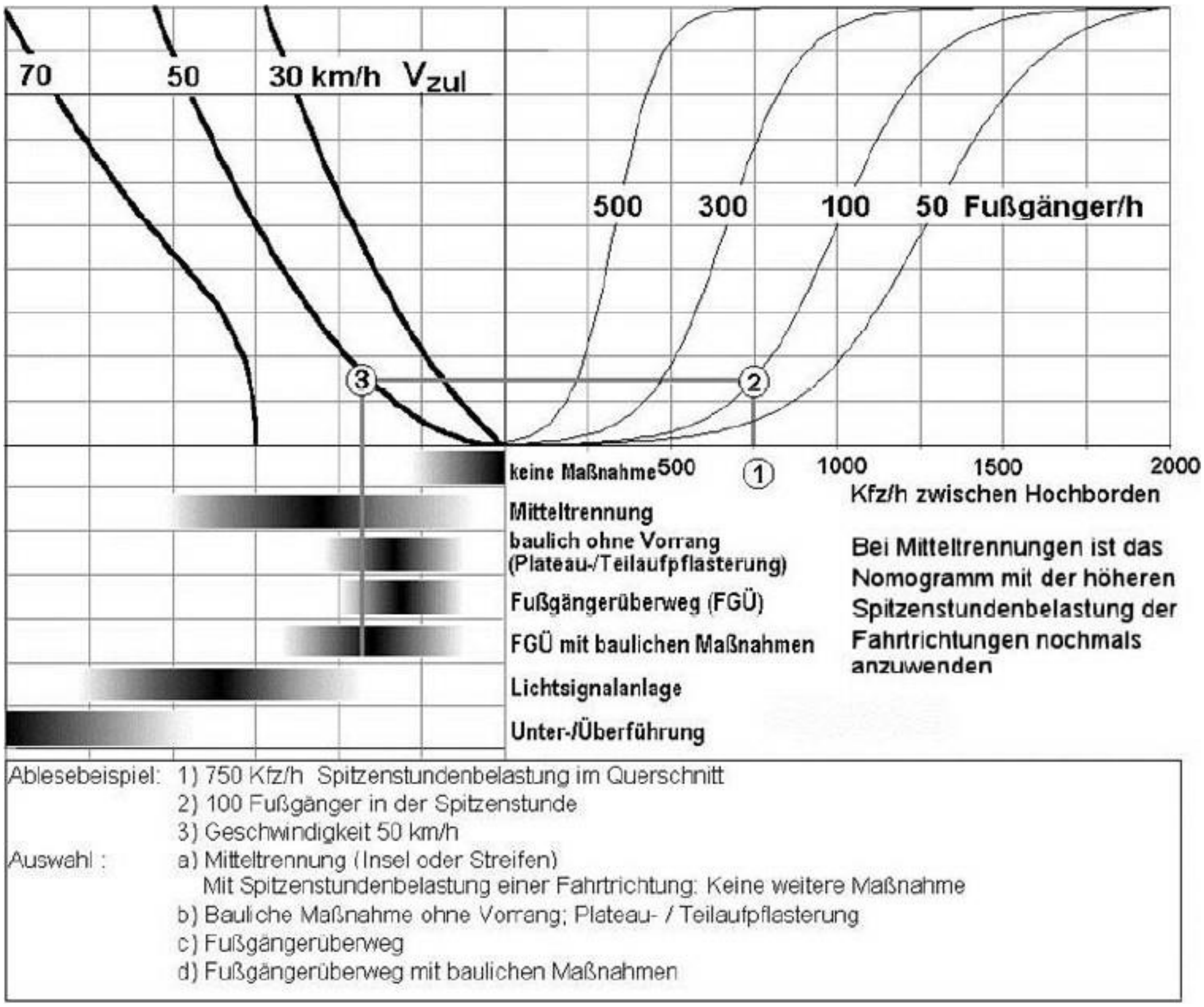


Figure 9.8: Utility of different pedestrian crossings across urban 2 lane roads. [36].

Kfz/h / Fg/h	0–200	200–300	300–450	450–600	600–750	über 750
0– 50						
50–100		FGÜ möglich	FGÜ möglich	FGÜ empfohlen	FGÜ möglich	
100–150		FGÜ möglich	FGÜ empfohlen	FGÜ empfohlen		
über 150		FGÜ möglich				

Figure 9.9: Suitability of pedestrian crossings in urban roads per pedestrian and vehicle peak. [36].

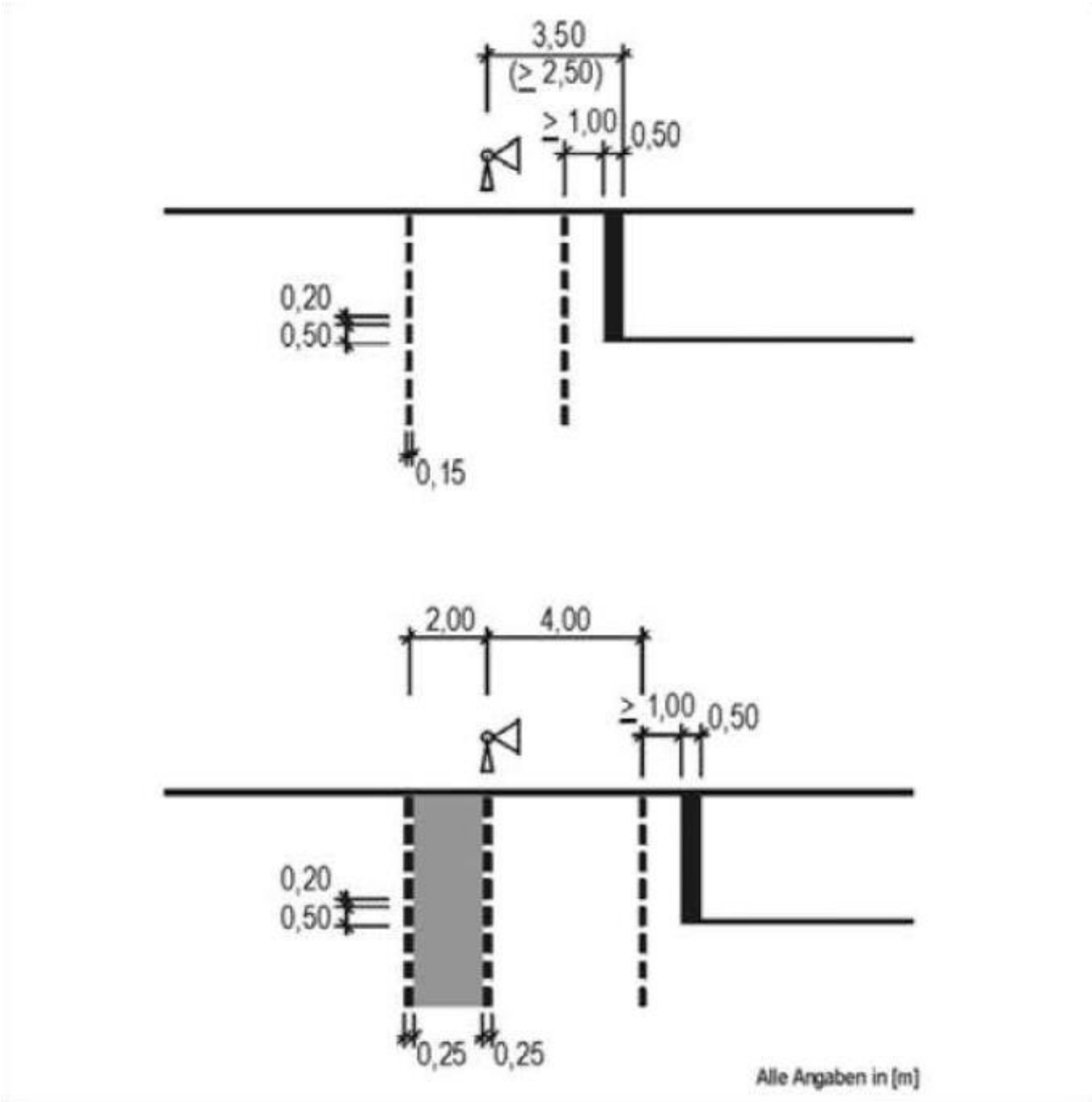
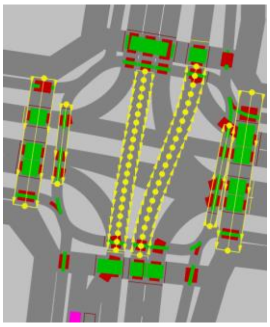
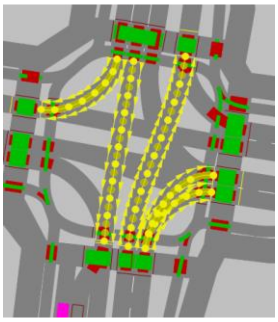
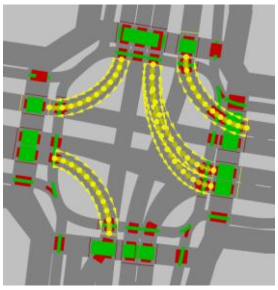
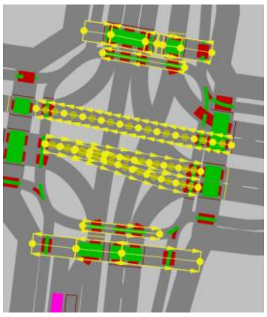


Figure 9.10: Standard dimensions for signalized pedestrian and bicycle crossings. [37].

Table 9.4: Calculation of the effective green phase times.

Element	Formula/Description/Value
$t_{F,erf,i}$	Minimum recommended effective green phase time: $$t_{F,erf,i} = \frac{q_{FS,maß,i} \cdot t_U}{q_{S,zul,i}}$$
$q_{FS,maß,i}$	Largest traffic demand in phase i in veh/h
t_U	Cycle time (either 72 or 90 seconds in Münster [3]) in hours
$q_{S,zul,i}$	Saturated flow directional capacity $$q_{S,zul,i} = 0.90 \cdot 1\,800 = 1\,620 \text{ (per lane)}$$

Table 9.5: Calculation of green times for alternative 1.

Phase	Recommended Minimum Green Time
1: North-South: 	$t_{F,erf,1} = \frac{85 \cdot 72}{1\,620} = 3.8$ Minimum effective green vehicles: 5 seconds Minimum green pedestrians: 8 seconds Minimum green time: 8 seconds Minimum full-red pedestrians: 7 seconds
2: North-South Turning: 	$t_{F,erf,2} = \frac{22 \cdot 72}{1\,620} = 1.0$ Minimum green time: 5 seconds
3: Turning: 	$t_{F,erf,2} = \frac{146 \cdot 72}{1\,620} = 6.5$ Minimum green time: 7 seconds
4: East-West: 	$t_{F,erf,3} = \frac{360 \cdot 72}{1\,620} = 16$ Minimum green time: 16 seconds

9.4 Appendix D: Results

Table 9.6: Final average measurements per criterion per alternative.

Criteria	Unit	Alt0	Alt1	Alt2	Alt3	Alt4
Safety						
Conflicts	# / d	97.0	15.2	35.4	4.0	82.2
TTC	s	1.76	0.424	2.49	1.94	1.62
PET	s	2.33	0.44	2.58	2.08	2.26
ΔS	m/s	2.67	4.27	8.39	9.28	6.73
DR	m/s^2	-0.666	0.363	-0.543	-0.689	-0.825
Points of Conflict	#	142	43	33	48	52
Conflict Danger	-	0.0426	0.0246	0.111	0.144	0.111
Conflict Motorized	°	6.98	3.74	11.3	2.74	2.79
Conflict Bicycle	°	27.7	8.10	17.5	4.28	1.79
Environment						
Vegetation Cover	%	12.90%	0.126	0.247	0.218	0.149
CO_X Emissions	g/d	33807	36451	15629	14299.33	39868
Total Area	m^2	13035	10302	10044	10490	7665
Sustainable Travel						
Cyclist Times	s	99.0	108	89.0	84.7	84.7
Bus Delays	s	20.9	41.2	11.2	5.05	9.64
Sustainable Travel	%	27.70%	0.468	0.490	0.474	0.694
Pedestrian Walk	s	106	119	101	98.9	106
Pedestrian Detours	m	19.8	29.6	31.7	28.5	38
Accessibility						
Vehicle Travel Time	s	54.7	78.0	56.6	79.4	64.3
Nighttime (19-6)	s	53.7	70.9	53.4	64.8	52.6
Morning Peak (6-8)	s	55.7	79.0	59.4	93.7	63.2
Regular Operation (8-16)	s	54.6	77.3	57.9	90.4	62.8
Afternoon Peak (16-19)	s	56.8	103	60.3	90.4	103
Max Queue	m	86.4	271	86.2	125	345

Table 9.7: Alternative scoring and weightings per criterion.

Criteria	Alt0	Alt1	Alt2	Alt3	Alt4	Weighting
Safety						9
Conflicts	0.0	0.8	0.6	1.0	0.2	6
TTC	0.0	-0.8	0.4	0.1	-0.1	7
PET	0.0	-0.8	0.1	-0.1	0.0	3
ΔS	0.0	-0.6	-2.1	-2.5	-1.5	3
DR	0.0	1.5	0.2	0.0	-0.2	5
Points of Conflict	0.0	0.7	0.8	0.7	0.6	5
Conflict Danger	0.0	0.4	-1.6	-2.4	-1.6	3
Conflict Motorized	0.0	0.5	-0.6	0.6	0.6	2
Conflict Bicycle	0.0	-0.7	-0.4	-0.8	-0.9	4

Environment						7
Vegetation Cover	0.0	0.0	0.9	0.7	0.2	4
CO_X Emissions	0.0	-0.1	0.5	0.6	-0.2	3
Total Area	0.0	0.2	0.2	0.2	0.4	5
Sustainable Travel						5
Cyclist Times	0.0	-0.1	0.1	0.1	0.1	7
Bus Delays	0.0	-1.0	0.5	0.8	0.5	5
Sustainable Travel	0.0	0.7	0.8	0.7	1.5	1
Pedestrian Walk	0.0	-0.1	0.1	0.1	0.0	4
Pedestrian Detours	0.0	-0.5	-0.6	-0.4	-0.9	2
Accessibility						3
Vehicle Travel Time	0.0	-0.4	0.0	-0.5	-0.2	2
Nighttime (19-6)	0.0	-0.3	0.0	-0.2	0.0	0
Morning Peak (6-8)	0.0	-0.4	-0.1	-0.7	-0.1	0
Regular Operation (8-16)	0.0	-0.4	-0.1	-0.7	-0.1	0
Afternoon Peak (16-19)	0.0	-0.8	-0.1	-0.6	-0.8	0
Max Queue	0.0	-2.1	0.0	-0.4	-3.0	3

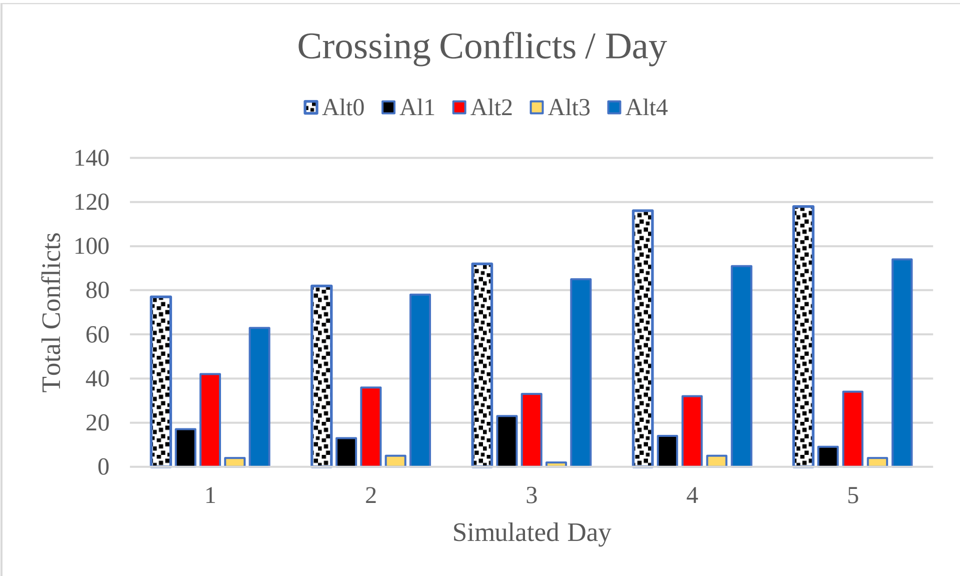


Figure 9.11: Crossing conflicts per simulated day and design alternative.

9.5 Appendix E: Sensitivity Analysis

9.5.1 Appendix E.1: Pedestrian Demand

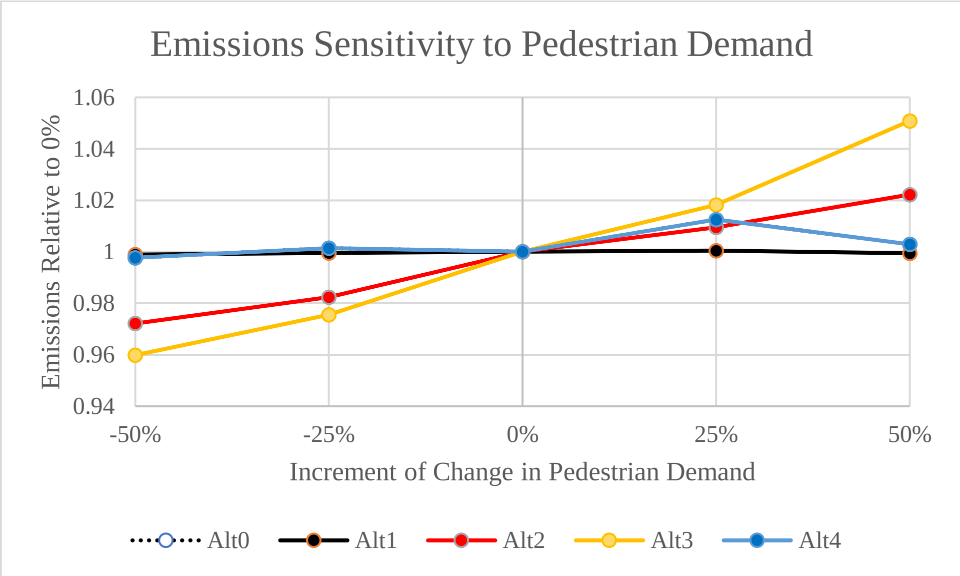


Figure 9.12: Emissions sensitivity to pedestrian demand per alternative.

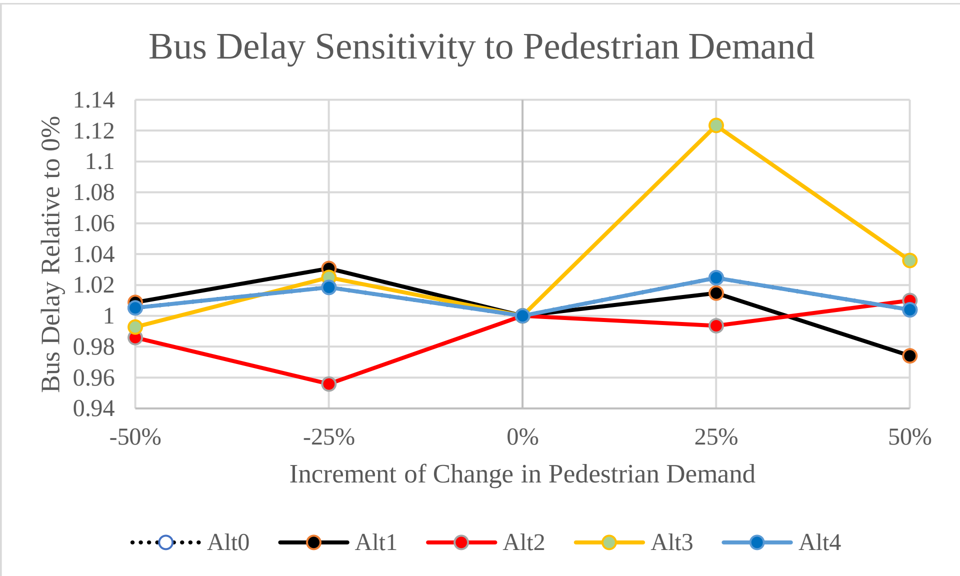


Figure 9.13: Bus delay sensitivity to pedestrian demand per alternative.

This figure shows that, due to the scarce buses traversing the intersection, individual incidents are more decisive in determining bus delay, rather than pedestrian demand.

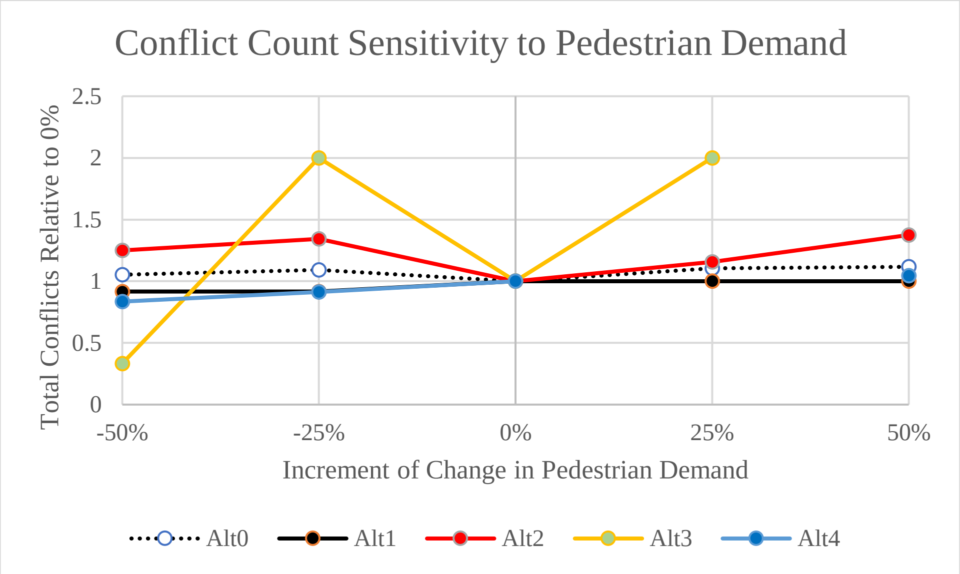


Figure 9.14: Conflict count sensitivity to pedestrian demand per alternative.

The models of alternatives three and four encountered errors when attempting to simulate 50% and 25% increases, respectively.

9.5.2 Appendix E.2: Overall Traffic Demand

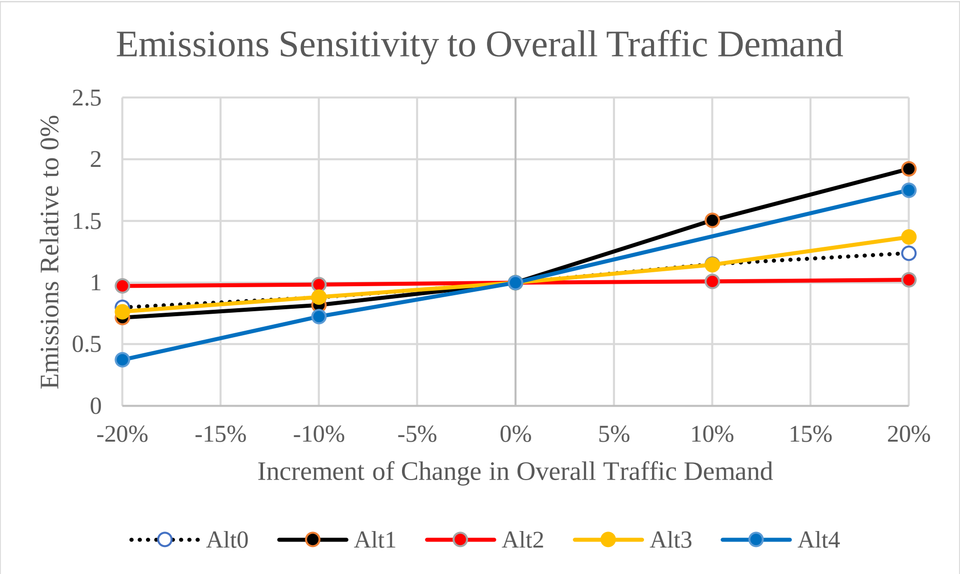


Figure 9.15: Emissions sensitivity to overall traffic demand per alternative.

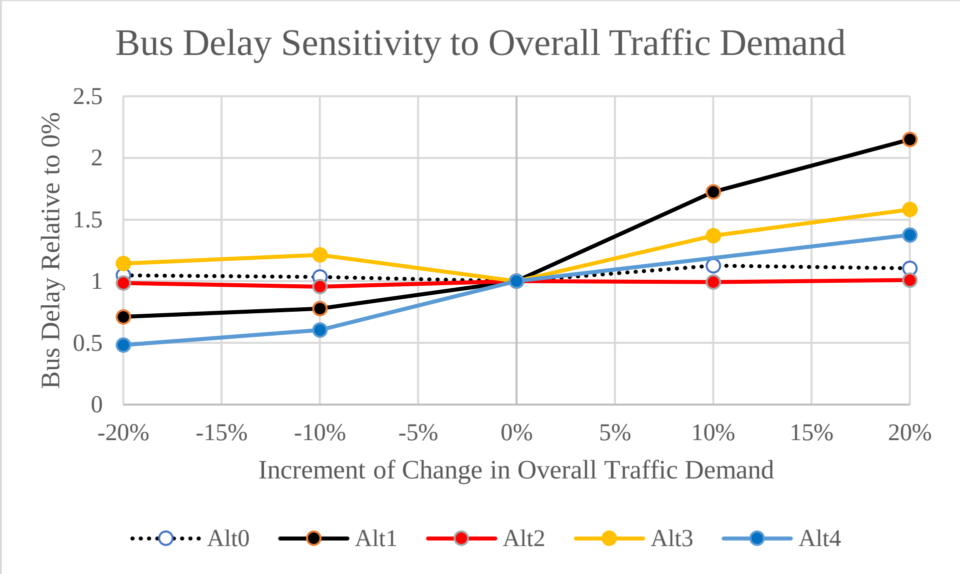


Figure 9.16: Bus delay sensitivity to overall traffic demand per alternative.

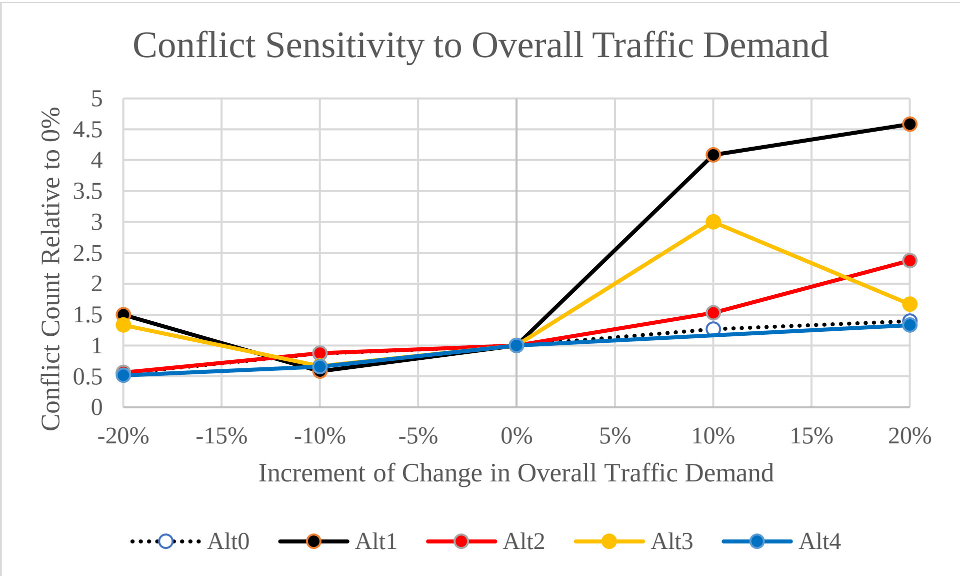


Figure 9.17: Conflict count sensitivity to overall traffic demand per alternative.

9.5.3 Appendix E.3: Conflict Angle Threshold

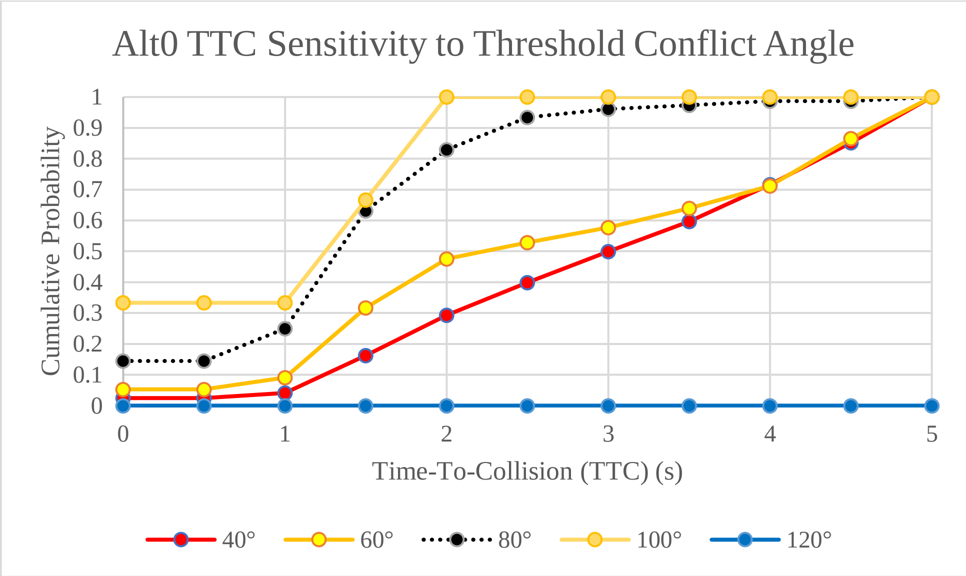


Figure 9.18: Current situation TTC sensitivity to threshold conflict angle.

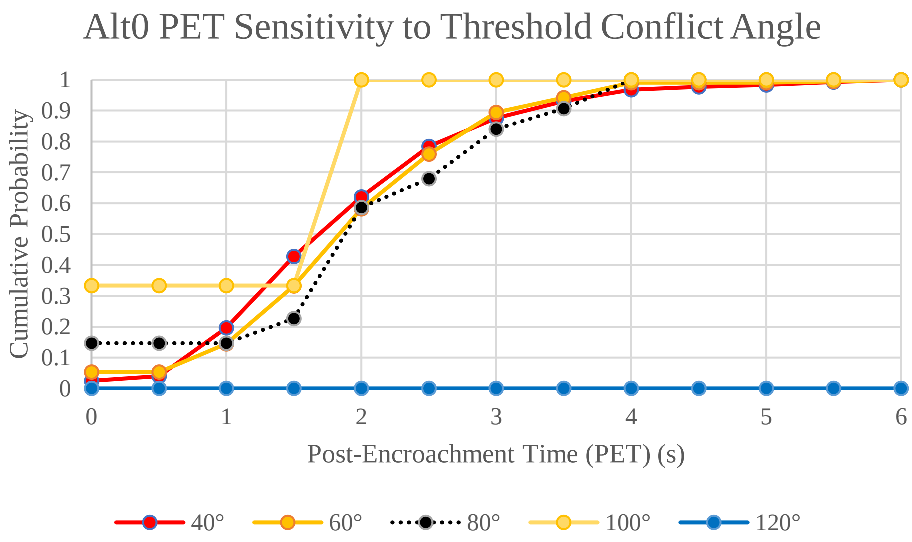


Figure 9.19: Current situation PET sensitivity to threshold conflict angle.

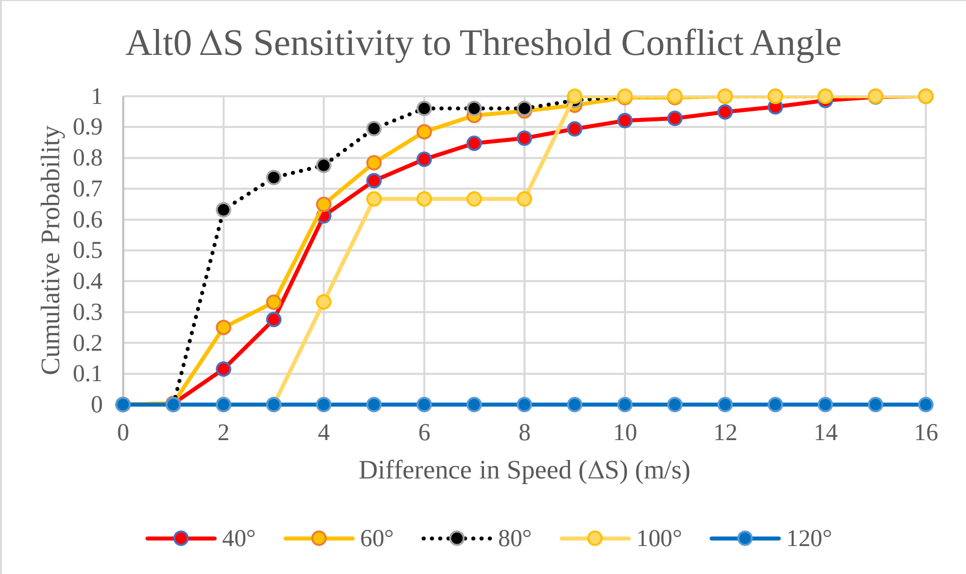


Figure 9.20: Current situation ΔS sensitivity to conflict threshold angle.

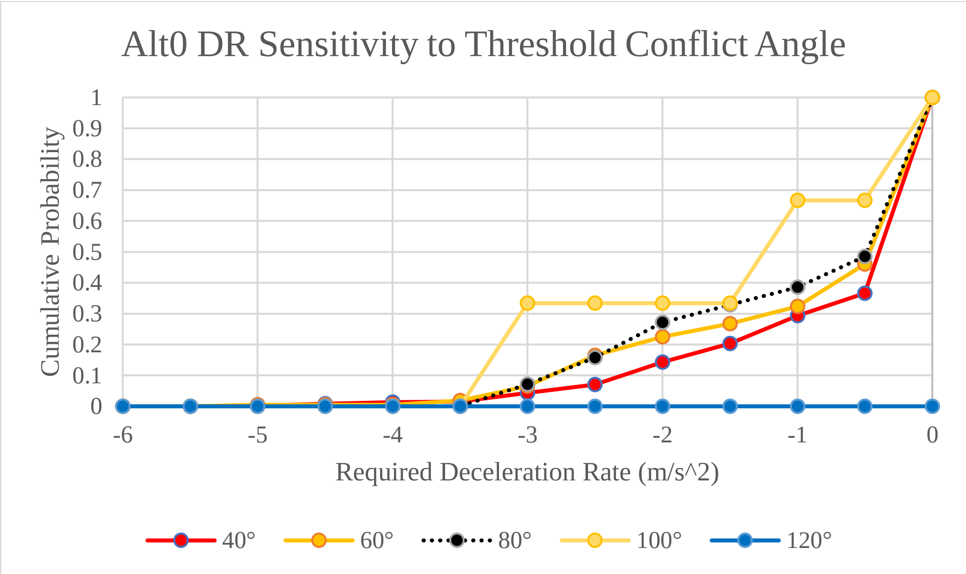


Figure 9.21: Current situation DR sensitivity to conflict threshold angle.

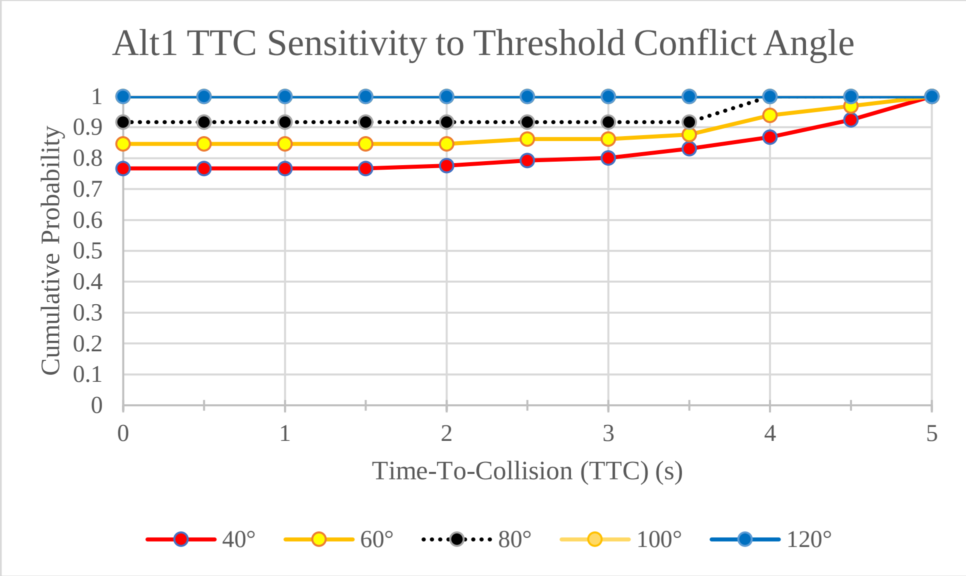


Figure 9.22: Alternative 1 TTC sensitivity to conflict threshold angle.

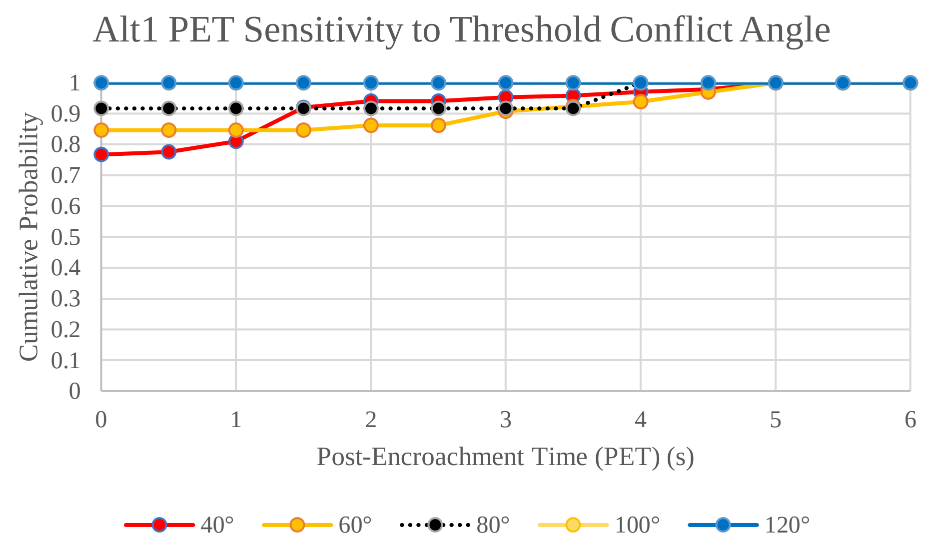


Figure 9.23: Alternative 1 PET sensitivity to conflict threshold angle.

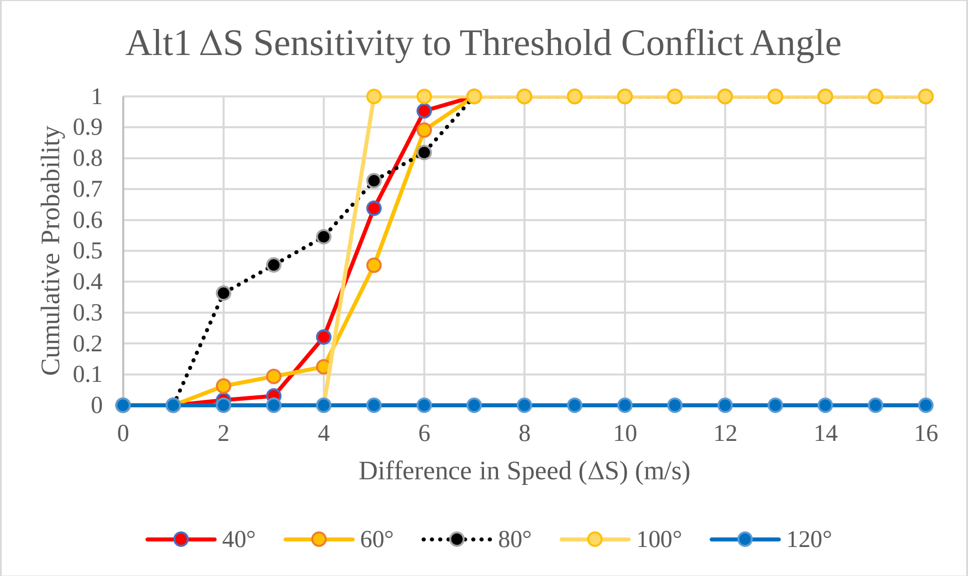


Figure 9.24: Alternative 1 Δs sensitivity to conflict threshold angle.

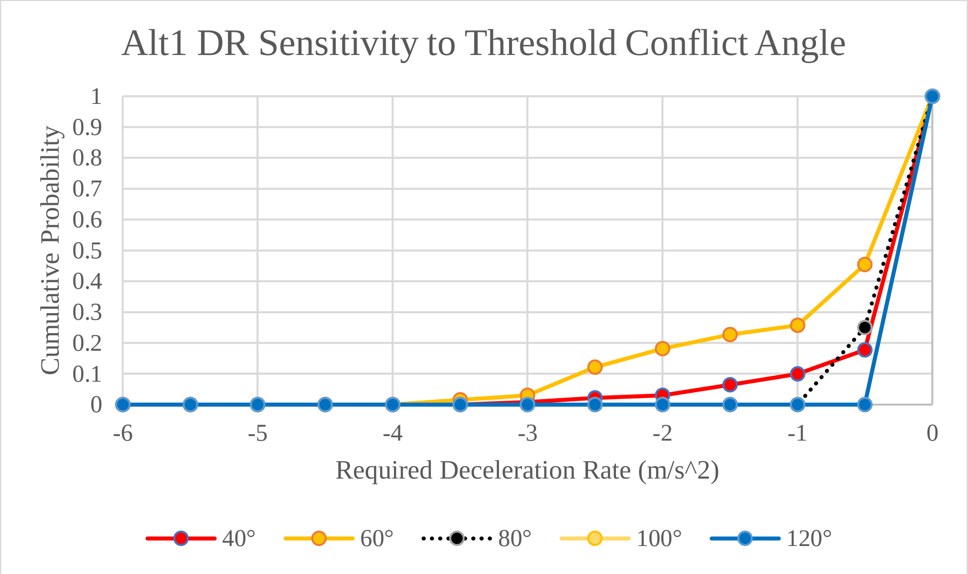


Figure 9.25: Alternative 1 DR sensitivity to conflict threshold angle.

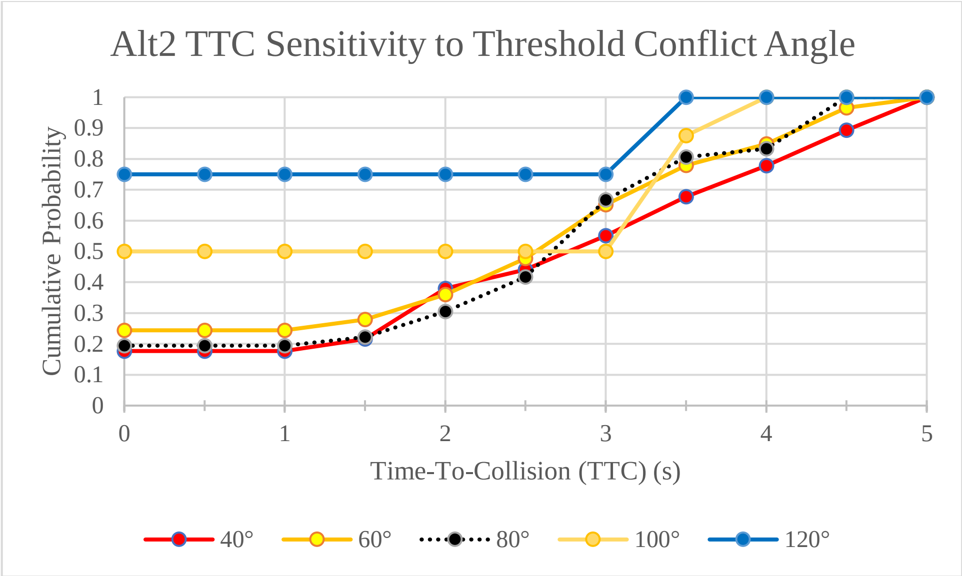


Figure 9.26: Alternative 2 TTC sensitivity to conflict threshold angle.

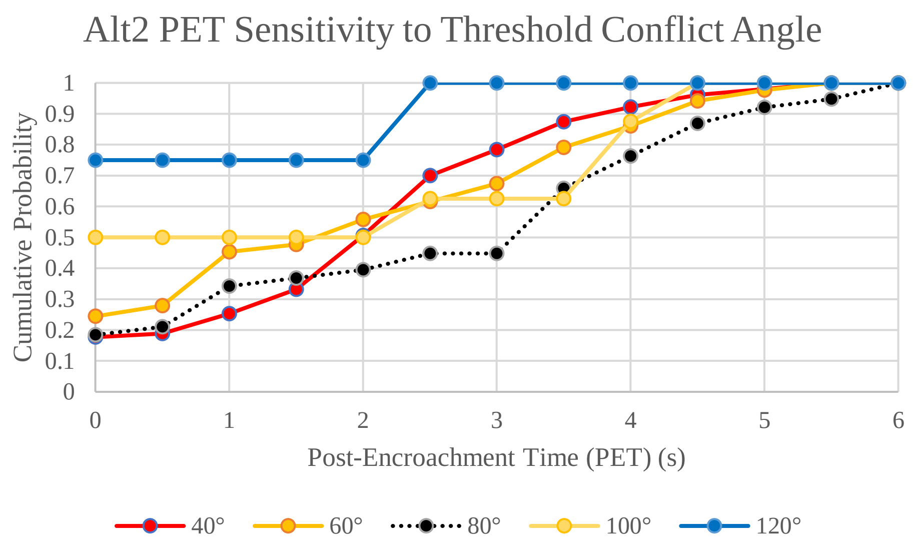


Figure 9.27: Alternative 2 PET sensitivity to conflict threshold angle.

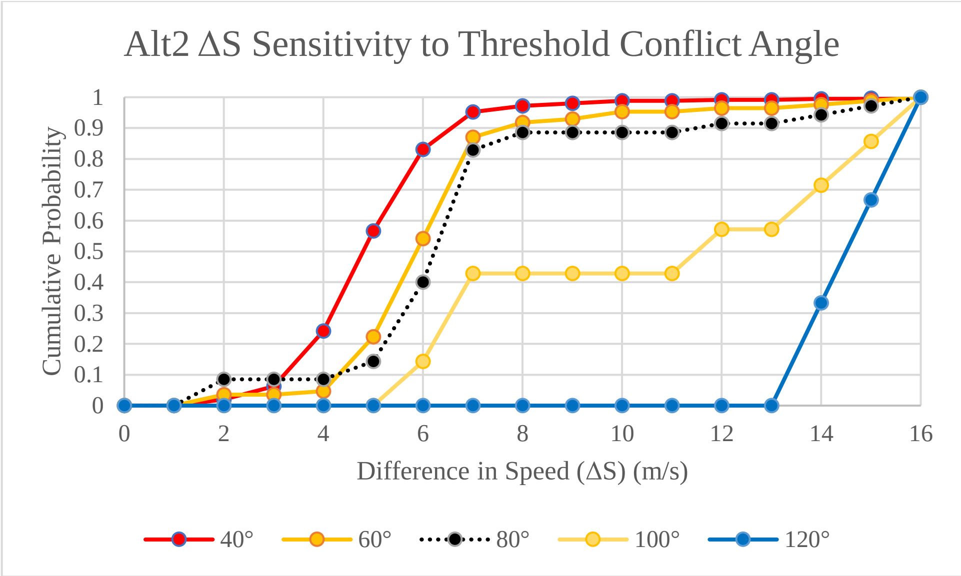


Figure 9.28: Alternative 2 Δs sensitivity to conflict threshold angle.

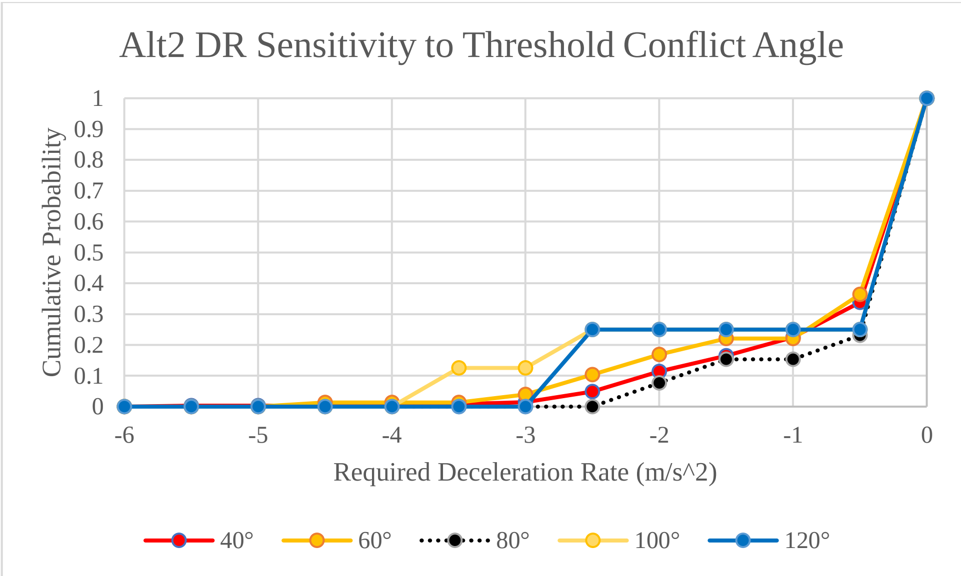


Figure 9.29: Alternative 2 DR sensitivity to conflict threshold angle.

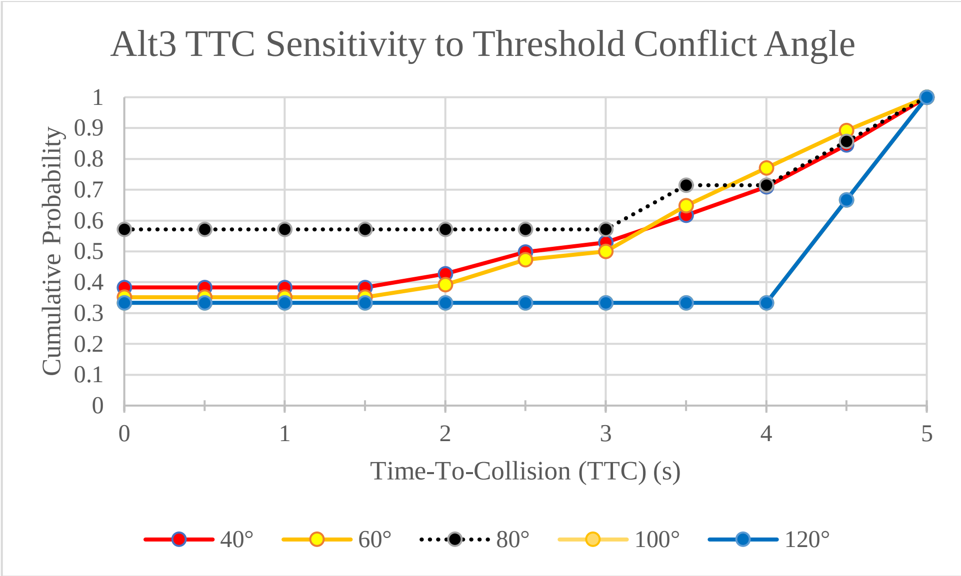


Figure 9.30: Alternative 3 TTC sensitivity to conflict threshold angle.

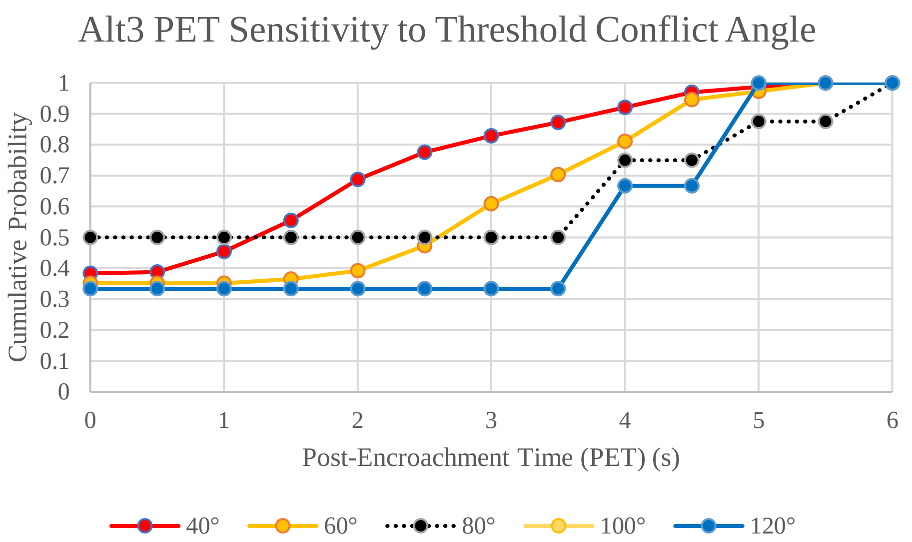


Figure 9.31: Alternative 3 PET sensitivity to conflict threshold angle.

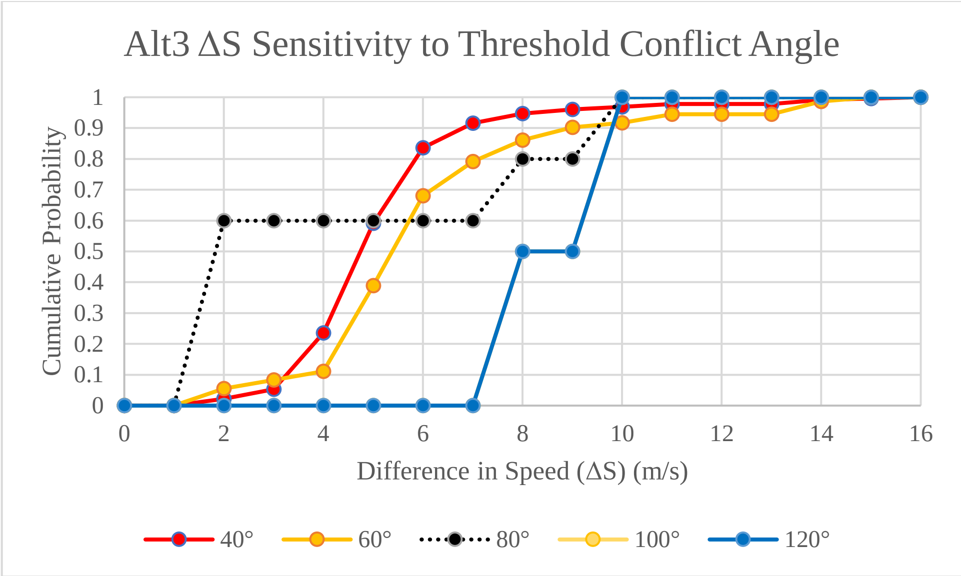


Figure 9.32: Alternative 3 Δs sensitivity to conflict threshold angle.

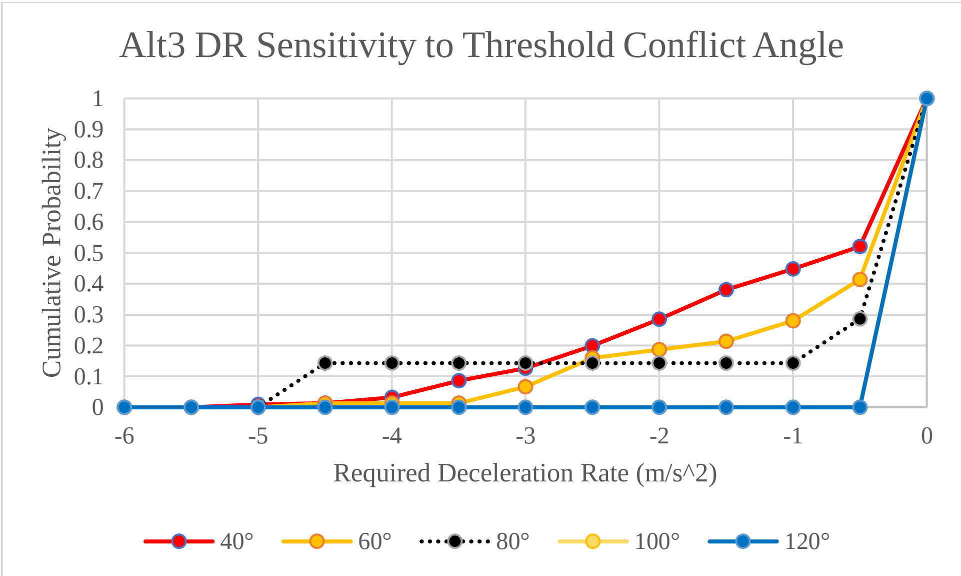


Figure 9.33: Alternative 3 DR sensitivity to conflict threshold angle.

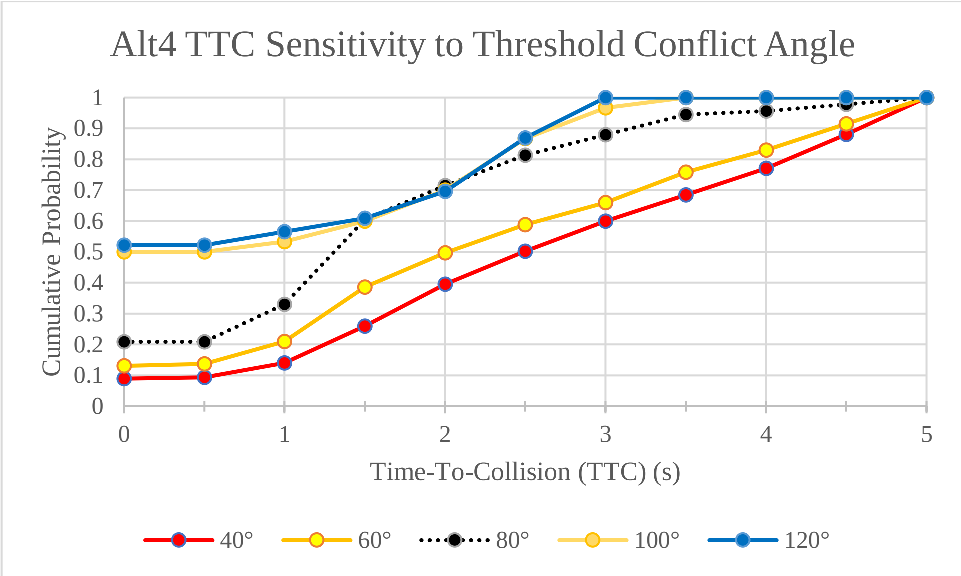


Figure 9.34: Alternative 4 TTC sensitivity to conflict threshold angle.

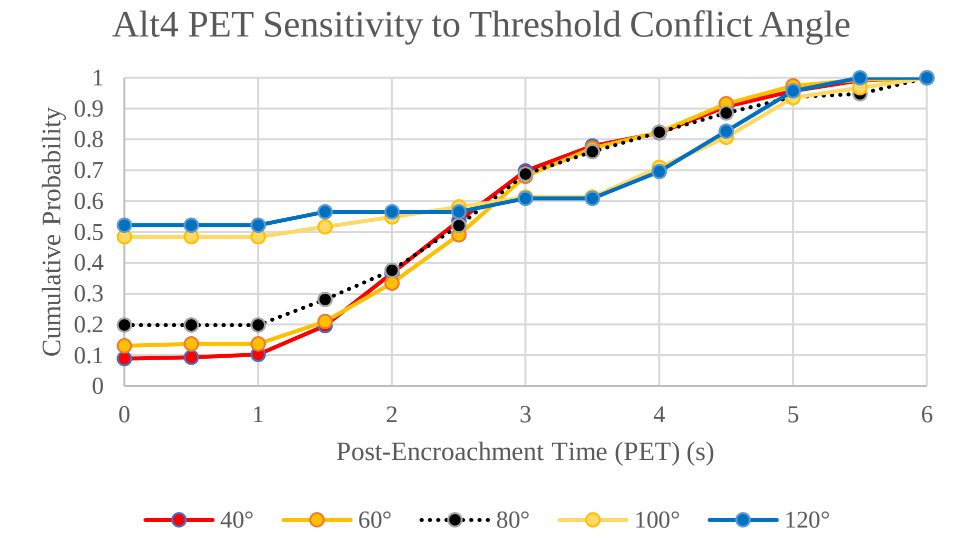


Figure 9.35: Alternative 4 PET sensitivity to conflict threshold angle.

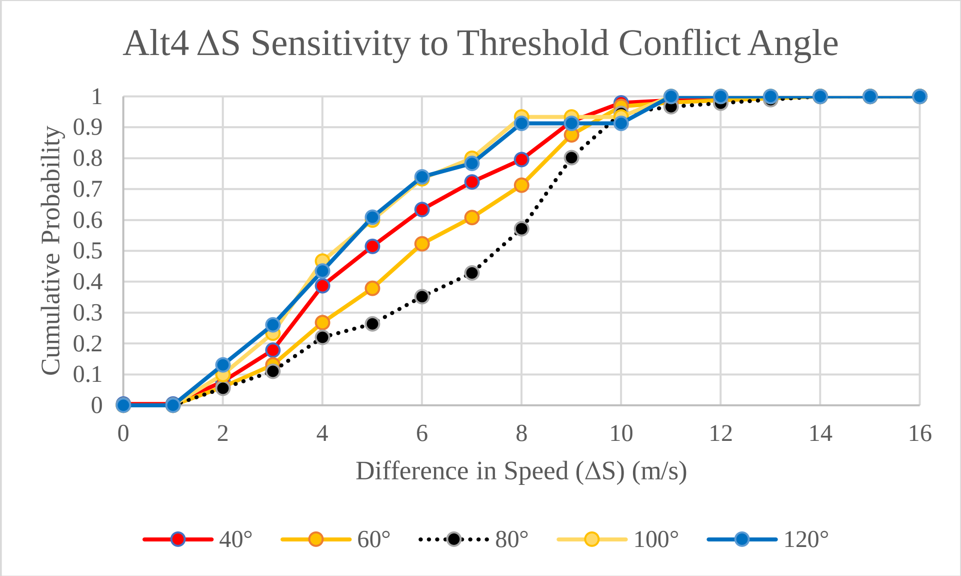


Figure 9.36: Alternative 4 Δs sensitivity to conflict threshold angle.

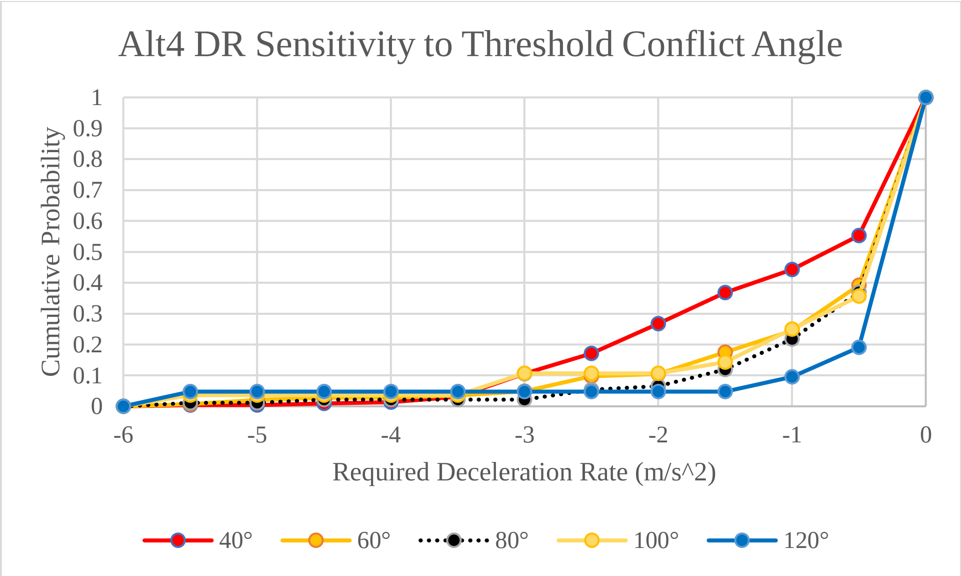


Figure 9.37: Alternative 4 DR sensitivity to conflict threshold angle.