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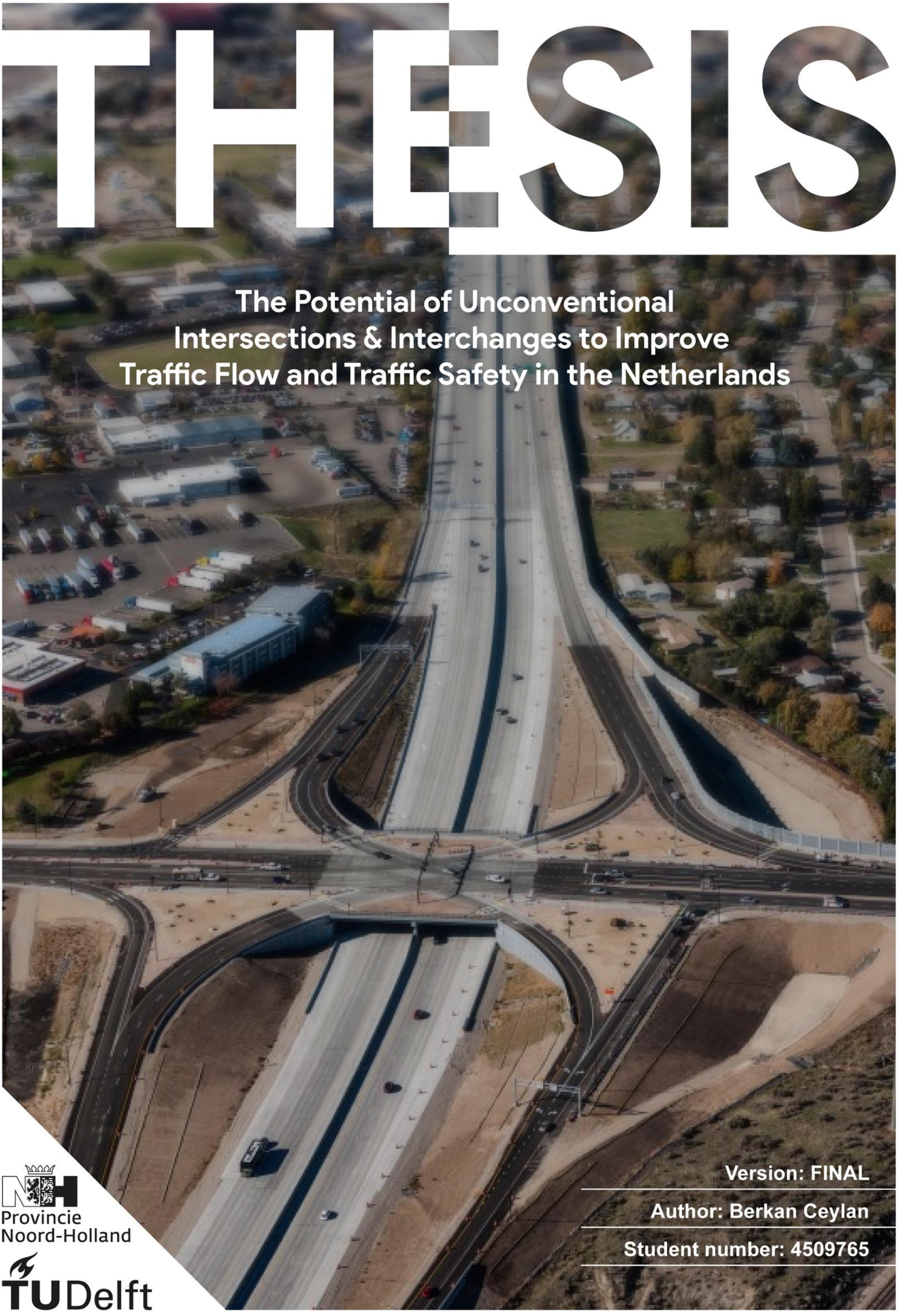

The Potential of Unconventional Intersections & Interchanges to Improve Traffic Flow and Traffic Safety in the Netherlands

Version: FINAL

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TU Delft

August 3, 2021
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The Potential of Unconventional Intersections & Interchanges to Improve Traffic Flow and Traffic Safety in the Netherlands

by

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In partial fulfilment of the requirements for the degree of

Master of Science
in Transport, Infrastructure and Logistics

at the Delft University of Technology,
to be publicly defended on August 18th, 2021.

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Acknowledgements

In front of you is the thesis 'The Potential of Unconventional Intersections & Interchanges to Improve Traffic Flow and Traffic Safety in the Netherlands', which I carried out at the end of my master's program in Transport, Infrastructure & Logistics, with the specialization 'Operations' at the Delft University of Technology. This report deals with various innovative forms of intersections and interchanges and gives an impression of how these designs can perform in the Netherlands. The research was conducted under supervision of the province of Noord-Holland. From March to July 2021, I was busy with this graduation research.

When I look back on conducting the research, I am satisfied with the result I have achieved. Mainly because I was able to do this during the pandemic, where I had to work remotely. Nevertheless, graduation generally went smoothly until I started working on the traffic models with an old license that turned out to have some limitations. Fortunately, while mailing around, I coincidentally came across with my former teacher who had taught me about PARAMICS during my bachelor. He was able to arrange a new license, which helped me to successfully generate results, allowing me to continue my research without delays. Therefore, I would like to thank Falco de Jong for his help.

Moreover, my graduation subject was very versatile. As a result, I had to stick to a tight schedule. Despite the fact that I had to work a lot in a limited time and sacrifice a number of weekends, I was fortunately able to finish it in time. All in all, it was a very instructive period in which I was able to apply and improve the knowledge I gained during my studies.

I would like to thank the supervisors from the province, Arjen Selhorst and Parvin Hoseini, for the intensive supervision during my graduation internship. We may have spoken less due to the pandemic, but you always answer my questions clearly and on time. I really appreciate this. In addition, I would like to thank all my other involved colleagues from the province for their enthusiasm, contribution, and useful tips for my graduation project.

Furthermore, I would like to thank Haneen Farah, Jan Anne Annema, and Henk Taale for the supervision from the university. You have always provided me with useful feedback and helped me to continuously improve my work.

Finally, I would like to thank my family for their support during my studies. Especially your support has made it possible for me to get this far!

Enjoy reading!

Berkan Ceylan
Zaandam, August 2021

Executive summary

The road quality in the Netherlands is experienced to be one of the best in the world. Despite this achievement, there is still room for improvement in terms of traffic flow and traffic safety. Especially in the coming years, the Netherlands faces the challenge of coping with the continuous increase in traffic volumes and reducing the number of road casualties. One of the ways to tackle this challenge is by adjusting/constructing new road infrastructure. When looking abroad, specifically in the United States, many intersection and interchange designs exist that have never been used before in the Netherlands. These designs are very different from the conventional ones and were initially designed to be an improved version of the traditional approaches. These American designs are also called *unconventional designs* and aim to reduce the travel time by rerouting left-turns. Subsequently, the number of phases of traffic signals reduces which improves the traffic flow. As the left-turns are rerouted, the number of conflict points reduces as well, which indicates an improved traffic safety.

Conclusions research questions

This study aimed at investigating whether unconventional designs, consisting of intersections and interchanges, have the potential to improve the traffic flow and traffic safety, under typical Dutch circumstances. This not only includes Dutch road characteristics and traffic volumes, but also includes the presence of pedestrians, cyclists, and public transport. The main research question is defined as follows:

What is the potential of unconventional intersections & interchanges to improve traffic flow and traffic safety in the Netherlands?

The potential is determined, compared to traditional solutions. Accordingly, the following sub questions are answered through the research study, which will contribute to answering the main research question. Before the main research question is answered, the sub questions SQ1-SQ4 composing the main research question are answered first.

SQ1. Based on theoretical advantages and disadvantages, which designs have the potential to be applied in the Netherlands?

A total of ten unconventional designs consisting of intersections and interchanges were analyzed to answer the first sub question of this research. The advantages and disadvantages were weighted up through a multi-criteria analysis, resulting in two intersections and two interchanges which are used for further research in this report. Examples why a certain design is not chosen are due to the lack of benefits, significantly high costs, or when it is too similar to another design that is already chosen. The following designs are chosen:

The Median U-Turn (MUT) is made up of one main intersection and two median crossover intersections. All left-turns are completed by making a U-turn by one of the median crossovers.

The Quadrant Roadway (QR) is made up of one main intersection and two secondary intersections that are connected with a connector road in any quadrant of the intersection. The left-turning vehicles at the main intersection are rerouted by using the secondary intersections and connector road, to complete left-turn movements.

The Diverging Diamond Interchange (DDI) is a grade-separated interchange where traffic from the suburban road navigates between the freeway ramps. Vehicles that want to make left-turns first move to the left side of the road between the ramps. As a result, it allows them to continue driving towards the on-ramps without conflicting with the opposing through traffic.

The Single-Point Urban Interchange (SPUI) is a variant of the conventional diamond interchange, where the two intersections have moved to the center, forming a single intersection. All the ramps begin or end at this signalized intersection on the suburban road. The right-turns on and off the ramps occur on bypasses to reduce the load on the main intersection.

Figure 1 Overview chosen designs

These are the four designs that are analyzed regarding their impact on traffic flow and traffic safety under Dutch conditions.

SQ2. If these structures were to be built in the Netherlands, the way they are in the United States, what are the necessary modifications to meet the Dutch criteria for traffic safety and road design guidelines?

A desk investigation is constructed using the Sustainable Safety principles, along with the American and Dutch design guidelines. Criteria of the Sustainable Safety principles are rephrased to questions which only the author of this study has given answer to for each of the designs, based on observations made through Google Maps/Street View. With the desk investigations, the necessary modifications are determined. These are shown below.

Table 1 Overview necessary modifications

	Observation American situation	Dutch circumstances
Physical separation between motorized traffic and slow traffic.	Not present	Necessary on roads where the maximum speed is at least 50 km/h
(Auxiliary) lanes	3.60 meters	3.0 to 3.10 meters
Narrow-paved shoulders	0.60 meters	0.30 meters

To conclude, all four designs meet the requirements set in the field of Sustainable Safety, provided that a number of plausible adjustments are made to the widths of the lanes. Each variant therefore has no critical peculiarity, which would make the application of the design in the Netherlands undesirable. For this reason, all four designs were included for further research in this study.

SQ3. What are the steps that need to be taken in order to introduce such new designs to the Dutch roads?

A workshop was held at the province. The audience consisted of members of different departments and sectors, among which road design, policy, traffic safety, management, and mobility. In a part of the workshop, two locations where the designs are tested on through traffic models, including the four designs themselves were presented. For each design the (yes/no) question was asked whether the experts found the design interesting for further research on the location. When the majority answered “yes”, an open follow-up question was asked. That is, SQ3.

The experts replied by saying “just do it”. It was mentioned that some small studies are necessary on beforehand, such as traffic psychology to determine how people respond to new infrastructural components such as the U-Turn. Further, it was recommended not to worry about adding these concepts to the CROW guidelines, as this might take years. Experience shows that innovative designs can be built without being added to the guidelines on beforehand.

SQ4. What is the impact of the selected designs on the traffic flow, traffic safety, and on its surroundings under Dutch circumstances?

Traffic models were built to investigate the potential of the chosen unconventional designs under Dutch circumstances. Two reference locations were chosen in the Netherlands, with one consisting of a traditional intersection with the presence of slow traffic and transit, while the other location consisted of a grade-separated Partial Cloverleaf (Parclo) Interchange. The designs in the current situations were then replaced by the chosen unconventional designs and analyses were performed regarding their impact on traffic flow, traffic safety, and the impact on their surroundings. By doing this, the fourth sub question of this research is answered. The following performance and safety indicators/measures were used:

Table 2 Overview of the performance indicators and safety measures

Traffic flow performance indicators	Surrogate safety measures
Travel times (all trips) Shows how fast traffic flows through the network.	**Time-To-Collision (TTC)** The time-to-collision during the conflict.
Travel time differences Indicates the effect of the designs on the possible delays occurring at the location.	**Post-Encroachment-Time (PET)** indicates the extent to which conflicting vehicles missed each other.
Vehicle counts The number of vehicles per period in the network.	**Deceleration rate (MaxD)** Deceleration of the second vehicle
Average distance travelled Indicates what impact rerouting has on travelled distances.	**Speed differentials (DeltaS)** Difference in speeds between consecutive vehicles.
	Conflict types Vehicle-vehicle crossing, merging, or diverging conflict points. Vehicle-cyclist/pedestrian conflict points are also considered. The number of conflict points (locations on the intersection/interchange where the paths of road users intersect) are illustrated.

All in all, the results illustrate that the unconventional designs prove to have benefits in terms of traffic flow and/or traffic safety, compared to their corresponding reference situation. An overview of the results is shown in the tables below. An indication is given whether the designs show a significant **improvement**, **deterioration**, or show **roughly the same** results, compared to their corresponding reference situation.

Table 3 Overview of the impact of the chosen designs on traffic flow

	Travel times (all trips)	Travel time differences	Vehicle counts	Average distance travelled
MUT	Improvement	Improvement	Improvement	Deterioration
QR	Improvement	Improvement	Improvement	Improvement
DDI	Improvement	Improvement	Improvement	Roughly the same
SPUI	Improvement	Improvement	Roughly the same	Roughly the same

Table 4 Overview of the impact of the chosen designs on traffic safety

	TTC	PET	MaxD	DeltaS	Conflict types (number of conflicts)
MUT	Improvement	Deterioration	Roughly the same	Improvement	Improvement
QR	Improvement	Deterioration	Deterioration	Deterioration	Roughly the same
DDI	Improvement	Improvement	Roughly the same	Roughly the same	Improvement
SPUI	Deterioration	Improvement	Roughly the same	Roughly the same	Roughly the same

Qualitatively, the impact of the designs on their surroundings was estimated as well. A brief summary of their impacts is depicted in the table below.

Table 5 Overview of the impact of the chosen designs on their surroundings

	MUT	QR	DDI	SPUI
Impact on surroundings	Small, mainly just adding U-Turns	Large, adding connector road	Large, different freeway ramps	Large, different freeway ramps, and reduction of intersections

All in all, it has been shown that under Dutch circumstances, the unconventional designs can provide major benefits in terms of traffic flow, traffic safety, and/or the impacts on their surroundings. It must be noted that each design has its own shortcomings, however, none of the designs perform significantly worse based on all three aspects. Hence, there was no necessity to drop certain designs.

Finally, with the sub questions being answered, the main research question is answered accordingly. The main research question is defined as follows:

What is the potential of unconventional intersections & interchanges to improve traffic flow and traffic safety in the Netherlands?

In short, it turned out that based on Sustainable Safety principles and design guidelines, only a small number of plausible adjustments in the width of the lanes are needed to adopt American unconventional designs in the Netherlands. These four designs also made a positive impression on the experts and professionals of the province Noord-Holland. Moreover, all four designs have shown positive results through traffic models, in terms of their impact on traffic flow, traffic safety, and/or impact on its surroundings, under Dutch circumstances. Furthermore, as mentioned during the workshop at the province, the efficient use of space of unconventional designs is a great benefit, especially with the increasing urbanization in the Netherlands. Customization is important regarding these innovative designs, meaning that they might not have many use cases in the province, however, on locations where these designs can be built (i.e., locations with the right amount of traffic from certain driving directions), they can have a large positive effect on the traffic situation in terms of improving the traffic flow, as well as the traffic safety, while remaining a compact design.

By way of conclusion, based on all the findings explored above, it has been proven that the unconventional designs for intersections and interchanges have great potential to improve the traffic flow and traffic safety in the Netherlands. However, it must be noted that some more studies are necessary before these designs can actually be built in the Netherlands. An example is a traffic psychology study to determine how road users experience unconventional designs. More about the recommendations can be read in the next section.

Recommendations for further research

Bowtie and Restricted Crossing U-Turn (RCUT)

The results of the traffic models have shown that the MUT has a great potential to improve the traffic flow and traffic safety. Hence, it is recommended to do some further research on designs that are similar to the MUT. Firstly, the Bowtie intersection. This is a type of intersection that is exactly the same as the MUT, but the U-Turns are replaced by roundabouts. Secondly, the RCUT, which is also very similar to the MUT, but where through movements from the side street also make use of the U-Turns. The RCUT was part of the ten designs this study initially started with.

Using SSAM to evaluate surrogate safety measures

The software tool SSAM can be used to determine surrogate safety measures, such as the number of crossing, merging, and diverging conflicts. To use SSAM, traffic modelling software must be used from which its output is compatible with SSAM, such as VISSIM. VISSIM can export trajectory files (.trj) that can be used in SSAM to determine the impact on of the designs on traffic safety more comprehensively.

More focus on slow traffic

Slow traffic (pedestrians and cyclists) was limitedly taken into account in this study. They were considered when determining the conflict points of each design. Further, slow traffic is only considered in the traffic signal schemes in the traffic models. This means that this study did not focus on how slow traffic experience new designs (i.e., traffic psychology). Moreover, the surrogate safety measures only applied to vehicles. Altogether, a recommendation is made to study traffic situations with the presence of slow traffic more explicitly.

Optimized traffic signals in traffic models

It must be noted that the seed values were not touched in the traffic models, and thus kept random. This means that in each simulation, vehicles enter the network at random times. Moreover, for each design only one simulation was run, while normally ten or more simulations are run. It is therefore recommended to either keep the same seed values for all models, or run multiple simulations per model, to gain more reliable results.

Further, applying green waves into the traffic models is something that can be done in further research to determine whether there are any differences in terms of efficiency of the traffic flow. It is also possible to go a step further by using smart traffic signals instead. Smart traffic signals (iVRI) work traffic-dependently, meaning that the signals and road users can communicate with each other. This in turn makes it possible to allocate green times even more efficiently. A possible recommendation is to combine the concept of the iVRI, with the unconventional designs in traffic models, and check how this impacts the traffic situation.

Recommendations made by the province for further research

During the workshop held at the province it was mentioned that, when wanting to build these unconventional designs in the Netherlands, some small studies are necessary on beforehand. One study that is mentioned is traffic psychology to determine how people experience new infrastructural components such as the U-Turn. The results of this study will provide more knowledge about how road safety is affected, based on possible driver confusion.

Moreover, it was mentioned that the surface of the U-Turns might wear out quickly due to the movements, especially caused by heavy vehicles. No studies were found regarding this topic in scientific literature. Hence, it would be an interesting topic for a follow-up study.

Determining quantitative cost estimations

This study has not comprehensively focused on the costs to build the designs. Instead, statements are made whether a design is expensive or not, based on their sizes and use of space. When considering these designs, costs can also play a role in the decision making. A possible (part of a) follow-up study could be doing a cost-benefit analysis for a reference situation, and compare this against other potential alternatives.

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AASHTO	American Association of State Highway and Transportation Officials
CGT	Continuous Green-T
CMF	Crash Modification Factor
CROW	Centrum voor Regelgeving en Onderzoek in de Grond-, Water- en Wegenbouw en de Verkeerstechniek
CTO	Center Turn Overpass
DDI	Diverging Diamond Interchange
DLT	Displaced Left-Turn
ERBI	Eisen en Richtlijnen Bouw- en Infraprojecten (Requirements and Guidelines Construction and Infrastructure Projects)
KiM	Kennisinstituut voor Mobiliteitsbeleid (The Netherlands Institute for Transport Policy Analysis)
MUT	Median U-Turn
NUUT	New Unconventional U-Turn
PET	Post-Encroachment Time
QR	Quadrant Roadway
RCUT	Restricted Crossing U-Turn
SPUI	Single-Point Urban Interchange
SSAM	Surrogate Safety Assessment Model
SWOV	Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (Dutch Institute for Road Safety Research)
TTC	Time-To-Collision

1
Introduction

According to the World Economic Forum (2019), the road quality in the Netherlands is experienced to be the second best worldwide, just behind Singapore, indicating that the road quality in the Netherlands is very extensive and efficient by international standards. Despite this achievement, there is still room for improvement in terms of traffic flow and traffic safety (KiM, 2020b; Ministry of Infrastructure and Water Management, 2018). The Netherlands Institute for Transport Policy Analysis (KiM) expects that due to the COVID-19 pandemic, in 2022, respectively 2023 the traffic volume can get up to the level of 2019 again. For the total traffic in the Netherlands, it is expected that in the year 2025, the volume will increase by 1-5.5% with respect to 2019. In the field of traffic safety, the minister strives for zero traffic casualties in 2050 (Ministry of Infrastructure and Water Management, 2018). On the other hand, a factsheet by the Dutch Institute for Road Safety Research (SWOV) shows that this goal cannot be reached if it is continued to work with the current methods (SWOV, 2018b).

Few general ways to improve the traffic flow and traffic safety are by policies influencing travel behavior such as fuel pricing, or by adjusting/constructing new road infrastructure. Due to costs, constructing new infrastructure is the least favorite option. However, if the problems are caused due to design-related issues, then the latter option may be preferred.

A research team of RTL news ("Steeds meer doden op kruispunten: elk jaar 20.000 ongelukken," 2019) showed through data analysis that about 24% of the accidents in a timespan of three years occurred at intersections. It is suggested that this is partly a design-related issue as the design guidelines are hardly used, especially on complex intersections where various road users are present. As a result, the recognizability of the roads are affected, causing confusion among the road users. In the Netherlands, when a new construction is considered, most road designers use the CROW guidelines for road design (CROW, 2013) to design the road environment. These guidelines mostly focus on traditional (conventional) approaches. Typical examples are three- or four-legged intersections, roundabouts, and diamond interchanges. When looking abroad, specifically in the United States, many intersection and interchange designs exist that have never been used before in the Netherlands. These designs are very different from the conventional ones and were initially designed to be an improved version of the traditional approaches. These American designs are also called *unconventional designs* and aim to reduce the travel time by rerouting left-turns. Subsequently, the number of phases of traffic signals reduces which improves the traffic flow. As the left-turns are rerouted, the number of conflict points reduces as well, which indicates an improved traffic safety.

These American designs are used before in other countries as well, for example, in Egypt. Study by El Esawey & Sayed (2011) compares the operational performance of several unconventional intersection designs with the conventional counterparts in Cairo, Egypt. The results indicate that the traffic situation improves in terms of level of service. It is shown that the studied alternatives reduce the overall delay and the total travel time, while the average speed increased. These findings show that the unconventional designs can perform well outside of the United States as well, but it does have to be noted that when comparisons are made with other countries, that differences exist in terms of traffic flow and traffic safety. Regarding traffic safety, Jagannathan (2007), who performed a study to determine the traffic safety on a Median U-Turn intersection (MUT), suggests that the number of collisions could possibly reduce by 20 to 50%, compared to a conventional intersection. The main safety benefit is a decrease in the likelihood of head-on and angle collisions, which often have high injury severity percentages. Of course, these numbers apply to American traffic situations, which might differ from Dutch circumstances. However, the results do indicate that an improvement over conventional variants is possible.

1.1. Problem statement

In the introduction it was stated that, based on traffic flow and traffic safety, the Netherlands still has room for improvement, whereby unconventional designs for intersections and interchanges could be seen as possible solutions. Prior to this study, a literature review was conducted. Reference is made to Chapter 2 of this report. Existing literature shows that different type of unconventional designs for intersections and interchanges exist that have never been used in the Netherlands. It is also shown that these designs, specifically built in the United States, have a positive impact on the traffic flow and traffic safety (see, Section 2.3.1 and 2.3.2). Additionally, reference is made as well to Appendix D, where design-specific impacts on the traffic flow and traffic safety are described.

Some of these American designs are built in other countries as well, but concerning the scoping, the focus of this study was only on the designs built in the United States. This way, only aspects such as, American road design and travel behavior had to be taken into account. No scientific literature exists that focuses on scenarios in Europe, specifically in the Netherlands. Only one evaluation was found of a Diverging Diamond Interchange, which was built for the first time in the Netherlands in 2019. It is claimed that due to the positive impacts of the design on the traffic flow and generally on the traffic safety, it is recommended to use this design more often in the Netherlands (Arcadis et al., 2020).

To check whether these findings also apply at other Dutch locations, and to check whether this is true for more designs, traffic models can be built to evaluate the impact of the designs on traffic flows and traffic safety at different Dutch locations. The use of space is also an important aspect that is necessary to be taken into account in a small, dense country. Furthermore, by using the Sustainable Safety principles, in combination with the Dutch and American guidelines for road design, built designs can be assessed on the extent to which they meet the Dutch criteria for road safety. This in turn determines the necessary modifications to use these designs in the Netherlands. All in all, research is needed to determine the potential of the unconventional designs in terms of improving traffic flow and traffic safety in the Netherlands.

1.2. Objective & research questions

The main objective of this study is to determine the potential of unconventional intersections and interchanges to improve the traffic flow and traffic safety, based on Dutch circumstances. This not only includes Dutch road characteristics and traffic volumes, but it is also aiming to include interactions with pedestrians, cyclists, and public transport. To achieve this goal a research question was proposed with several sub questions. The main research question is defined as follows:

What is the potential of unconventional intersections & interchanges to improve traffic flow and traffic safety in the Netherlands?

The potential is determined, compared to traditional solutions. Accordingly, the following sub questions are answered through the research study, which will contribute to answering the main research question.

- SQ1. Based on theoretical advantages and disadvantages, which designs have the potential to be applied in the Netherlands?
- SQ2. If these structures were to be built in the Netherlands, the way they are in the United States, what are the necessary modifications to meet the Dutch criteria for traffic safety and road design guidelines?
- SQ3. What are the steps that need to be taken in order to introduce such new designs to the Dutch roads?
- SQ4. What is the impact of the selected designs on the traffic flow, traffic safety, and on its surroundings under Dutch circumstances?

1.3. Scope of this research

This study focuses on the geometrical design of intersections and interchanges. First, it is important to make a clear distinction between what conventional and unconventional designs are. Conventional designs are the type of structures that are commonly used in the Netherlands. Typical examples are three- or four-legged intersections, roundabouts, and diamond interchanges (Haarlemmermeeraansluitingen). There are also certain unconventional designs that are used in the Netherlands, such as turbo roundabouts, or the LARGAS-roundabout (Langzaam Rijden Gaat Sneller) in Hilversum (Municipality Heuvelrug, 2010). Furthermore, when looking abroad, specifically in the United States, many unconventional designs exist that have never been used before in the Netherlands. These designs are also very different from the conventional ones mentioned before. Unconventional designs were initially invented to be an improved version of the traditional approaches. Most of these designs aim to reduce the travel time and improve the traffic safety by rerouting left-turns. Subsequently, the number of phases of traffic signals reduces which improves the traffic flow. As the left-turns are rerouted, the number of conflict points reduces as well, which indicates an improved traffic safety.

Regarding the scoping of this study, only the American designs are taken into account. This has several reasons. First of all, if more countries are taken into account, also their specific traffic rules, data and travel behavior need to be considered in this study, which would significantly increase the workload and complexity. Moreover, many scientific papers and information is available about the American variants. For these reasons, the focus in this study is on American designs only.

Reference is made to Appendix A where a total of ten unconventional designs from the United States are briefly discussed. These are the following:

- Intersections:
    - Center Turn Overpass
    - Continuous Green-T
        - Also known as the Seagull Intersection
    - Displaced Left-Turn intersection
        - Also known as the Continuous Flow Intersection
    - Echelon
    - Median U-Turn
        - Also known as the Michigan Left-Turn
    - Quadrant Roadway
    - Restricted Crossing U-Turn
        - Also known as the Superstreet Intersection
- Interchanges:
    - Displaced Left-Turn Interchange
        - Also known as the Continuous Flow Interchange
    - Diverging Diamond Interchange
        - Also known as the Double Crossover Diamond
    - Single-Point Urban Interchange

More alternative designs exist for intersections as well as interchanges. For example, the Texas U-turn and the Michigan Urban Diamond (Dixon et al., 2018; Virginia Department of Transportation, 2021). These are examples of state-specific designs and have certain characteristics that makes it not easy to use in the Netherlands. Both the examples are only beneficial in situations where the road network is designed as a grid. This is very common in the United States, unlike in the Netherlands. The ten designs that are included are often mentioned in various governmental reports and scientific articles. Some of these designs are used nationally (in the US), as well as internationally, such as the Median U-Turn (El Esawey & Sayed, 2011; El Esawey & Sayed, 2013). Further, there are certain designs that are very similar to each other. To keep the number of similar designs low and the versatility high, it was considered to disregard certain designs. An example is the Bowtie intersection. This is a type of intersection that is exactly the same as the Median U-Turn, but the U-Turns are replaced by roundabouts. The idea for this study was, given the MUT being for further research, to do a research on only the MUT from these similar designs. If it turned out that the MUT had potential to be implemented in the Netherlands, the chances would be high that it would also apply to designs that are similar. Then, the similar designs would be mentioned for further research in the Recommendations section. For these reasons and to keep the workload feasible, this study is limited to the ten designs that are discussed the Appendix A.

The scope from a geographical point of view, as can be derived from the main research question, is the Netherlands. This means traffic data is used coming from Dutch locations.

The impact of the unconventional designs on the traffic flow, traffic safety, and on its surroundings are determined by building and simulating traffic models. The traffic models are built as relatively small networks with the intersection/interchange being the main point of interest. In this case the traffic models are built on a microscopic level, which makes it possible to represent traffic behavior more realistically in congested situations, but also on individual vehicle level. Furthermore, not only motorized vehicles, but also pedestrians and cyclists are taken into account to make it resemble Dutch circumstances even more. Whenever possible, the presence of transit is also taken into account.

Beforehand, a brief summary was made discussing a total of ten unconventional intersections and interchanges. These can be found in Appendix A. Later in this study, a multi-criteria analysis is conducted to answer the first sub question. Accordingly, the number of designs is reduced to an appropriate number that fits the time schedule. It will consist of two intersections and two interchanges. Regarding the traffic modelling, locations in the Netherlands are chosen where these designs can be built. In an ideal situation, one location is chosen where its intersection can be replaced by all intersection designs, and another location where its interchange can be replaced by all the interchange designs. The characteristics of the locations and the designs play a role in choosing the locations. Aspects such as the number of connections of the current intersection/interchange, the amount of space, and the presence of slow traffic and public transport are considered when choosing the locations.

1.4. Thesis outline

The thesis is structured as follows:

2. **Literature review**, conducted prior to the thesis activities. The objective and research questions are set up based on this literature review. It also forms the base of the methodology, which can be found in the next chapter.
3. **Research design** outlines the research methodology and the data analysis that is carried out subsequently.
4. **Potential designs for further research**, are identified, through a multi-criteria analysis. The results consist of two intersection and two interchange designs.
5. **Sustainable Safety evaluation** presents the results of the desk investigation, which will show the extent to which unconventional designs that are built in the United States, meet the Dutch Sustainable Safety principles. This leads to necessary modifications.
6. **Traffic models study**, shows the impact of the chosen unconventional designs on traffic flow, traffic safety, and the impact on its surroundings.
7. In the chapter for **Discussion**, the research limitations and assumptions are discussed. Also, the contribution of the presented study is mentioned.
8. **Conclusions and recommendations**, outlines the conclusions that are drawn resulting from this study. The research questions in this chapter are also answered and the entire research is evaluated. Finally, suggestions are made for possible further research.

2
Literature review

The focus in this literature review is to find whether there are problems related to traffic in the Netherlands, such as congestion or traffic safety related issues, where unconventional designs could play a role in improving the traffic situations. Based on this, it can be determined whether it is useful to answer the main research question with the help of this research. This chapter provides theoretical background, which was used to set up the research questions, mentioned in Section 2.1.2. Subsequently, this literature review shall form a base to determine the methodology of the study.

This chapter first describes traffic-related issues in the Netherlands (i.e., traffic flow and traffic safety issues) in Section 2.1. Hereafter, a suggestion is made to solve these issues with the introduction of unconventional designs for intersections and interchanges, in Section 2.2. Moreover, topics that need to be studied in order to introduce unconventional designs in the Netherlands are discussed in Section 2.3. Finally, this chapter end with a brief summary, mentioning the takeaways from this literature review.

2.1. Traffic-related issues in the Netherlands

Unconventional designs can have advantages related to traffic flow and traffic safety. Hence, it is important to find out whether there are actual issues related to these two aspects in the Netherlands. This is explained in this section.

2.1.1. Traffic flow in the Netherlands

KiM (2020b), the Netherlands Institute for Transport Policy Analysis, expects that in 2022, respectively 2023 the traffic volume can get up to the level of 2019 again. For the total traffic in the Netherlands, it is expected that in the year 2025, the volume will increase by 5.5% with respect to 2019. If the COVID-19 pandemic lasts longer, it is expected that more activities such as meetings and learning will take place online in the longer term, thereby slowing down growth in traffic volume and loss of travel time. Another report by KiM (2020a), analyzed through a questionnaire the seriousness of traffic jams from the perspective of the Dutch citizen. The results show that in 2019, traffic jams are only a limited societal problem. Compared to 2010, the acceptability of traffic jams of the Dutch population decreased from 72% to 35%. From the respondents’ perspective, aspects like traffic safety is seen as a bigger problem than traffic jams. Despite the fact that some of the respondents experience feelings of stress, frustration and irritation, acceptance and resignation are the strongest feelings in the (daily) traffic jam.

Based on the two reports, it can be concluded that due the growth in traffic volume the road infrastructure needs to be optimized accordingly. Drivers do have some acceptancy for traffic jams, but aspects like traffic safety deserve at least as much, if not more, attention than the reduction of congestion.

2.1.2. Traffic safety in the Netherlands

As discussed in the previous section, traffic safety issues are important to take into account when designing roads. In terms of traffic safety, the national goal in 2020 was to have a maximum of 500 traffic fatalities and 10,600 serious traffic injuries (Ministry of Traffic and Water Management, 2008). No goals are set yet for 2030, however, the minister strives for zero traffic casualties in 2050 (Ministry of Infrastructure and Water Management, 2018). Currently, there are still 21,000 serious traffic injuries yearly. At a yearly average reduction of 14% would mean that in 2050 the number of serious traffic injuries equals 200 (SWOV, 2018b). Moreover, one of the proposed actions (related to this study) are improving the traffic safety on N-roads, as one in five traffic fatalities occurs in an accident on a provincial road (Ministry of Infrastructure and Water Management, 2018). Altogether, it is shown that there is still room for improvement in terms of traffic safety.

Furthermore, cyclists play an important role in traffic of the Netherlands. When designing roads in urban areas, cycle paths are also taken into account. When looking at the modal split, the share for bicycles is estimated to be approximately 27% of all the trips made by Dutch citizen (Harms et al., 2014). Research by Boufous and Olivier (2015) shows an increasing trend in bicycle deaths with no motorized vehicles involved, while a decreasing trend is found for bicycle-motorized vehicle crashes in Australia. Accordingly, a subsequent study conducted by Schepers et al. (2015) mentions a similar trend in the Netherlands.

In general, it is assumed that most road fatalities among cyclists are the result of accidents involving motorized vehicles and cyclists (Schepers et al., 2015). On the contrary, another study by Schepers et al. (2017) shows that cyclist deaths caused by an interaction with motorized vehicle crashes decreased in 1996–2014 while bicycle deaths with no motorized vehicles involved increased. Despite the high investments in safer infrastructure (Twisk et al., 2016), the number of deaths among cyclists did not change significantly during the last decade from 2017. A possible cause could be due to increased number of elderlies who cycle and the speed of cyclists (with e-bikes).

The previously mentioned reports show that the traffic safety can be improved on the Dutch roads, but do not mention the cause of the traffic casualties. Therefore, it is unknown whether the road design plays a role in these accidents. A research team of RTL news ("Steeds meer doden op kruispunten: elk jaar 20.000 ongelukken," 2019) used data (Rijkswaterstaat & The Netherlands Police, 2016–2018) that consists of yearly registered road incidents. They filtered out the number of accidents to just the accidents that have occurred at intersections. Based on about 250,000 accidents in three years (2016-2018), more than 60,000 occurred at intersections. This equals 24% of all the incidents. It is suggested that this is partly a design-related issue as the design guidelines are hardly used, especially on complex intersections where various road users are present. As a result, the recognizability of the roads are affected, causing confusion among the road users. Traditional designs for intersections thus have shortcomings. Based on these observations, unconventional designs can play a role in improving the traffic safety. In general, unconventional designs have a reduced number of conflict points, compared to its conventional counterpart. Conflict points are locations at an intersection where the paths of vehicles merge, diverge, or cross each other. Therefore, the reduced number of conflict points could translate to fewer collisions.

2.2. Unconventional intersections and interchanges to solve traffic-related issues in the Netherlands

In the previous section it is mentioned that there are (future) traffic-related issues in the Netherlands. Therefore, it is possible that unconventional designs might be able to solve these issues. But first, a brief introduction is given related to these designs. It is discussed to what extent already is known about these designs in the Netherlands. Also, whether these designs have been built before outside of the United States and how they perform there. This section ends with an overview of all reviewed literature regarding unconventional designs considered in this study.

2.2.1. Unconventional intersections and interchanges

When looking abroad, many intersection and interchange designs exist that have never been used in the Netherlands. In the United States, these designs are also called unconventional designs. In section 1.3, it is indicated that many of these innovative designs are designed and built there. Therefore, much information is available about these American variants.

The reasoning behind why many of these designs have never been considered in the Netherlands is unknown. However, even in the United States these unconventional designs are not used as much as expected despite their benefits. The paper by Shumaker et al., (2012) has documented barriers to use unconventional designs. The survey that is conducted shows that the public’s main concerns are driver confusion and fear of the unknown. On the other hand, the survey responses and interviews show education is an important factor, and that public opinion of unconventional designs improves once such designs are constructed and experienced. This suggests that as more of these unconventional designs are built, the public opposition will decrease. It is possible that these outcomes are also applicable to the Netherlands.

New intersection designs exist in other countries as well. For example, in China, a NUUT-intersection (New Unconventional U-Turn intersection) was introduced recently (Pan et al., 2020). This is a modified version of what already exists in the United States, a Median U-Turn intersection, but with the advantage that a distinction is made at the U-turn for small and large vehicles. Other examples can be found in countries, such as Egypt (El Esawey & Sayed, 2011), France (Siromaskul, 2010), and recently in the Netherlands as well (GWW, 2020). In the Netherlands, the Diverging Diamond Interchange (DDI) was temporarily built to keep the Leiden-West connection accessible during the road works on the RijnlandRoute. An evaluation of this interchange shows that the DDI functions properly in terms of traffic safety (Arcadis et al., 2020). The reverse driving directions do not cause major problems. There is only an unclear situation when the traffic signals fail, leading to road safety risks. The other findings regarding human factors and traffic safety mainly relate to location-specific characteristics and not so much to the DDI itself. Lastly, it is mentioned that the traffic flow has improved after the realization of the DDI. Due to the positive impact of the DDI on the traffic flow and in general on the traffic safety, it is recommended to use this design more often in the Netherlands.

2.2.2. Literature overview unconventional designs

According to the available literature, every unconventional design has its advantages, disadvantages, and application domain. As mentioned before, these can be found in Appendix A. Also, literature was used to motivate the scores that are allocated in the multi-criteria analysis. Reference is made to Appendix D for the motivations. Table 6 depicts all the reviewed literature related to unconventional designs. Each source is categorized by the purpose and the type of design the source focuses on. Subsequently, a more detailed table (Table 29) is created that also summarizes the main findings of each reviewed source that are relevant for this study. This can be found in Appendix C.

Table 6 Literature overview

	General (various characteristics)	Traffic flow impacts	Traffic safety impacts	Unconventional designs outside of the US
General (multiple designs)	(Virginia Department of Transportation, 2021) (Hughes et al., 2010) (Shumaker et al., 2012) (El Esawey & Sayed, 2013) (Tarko et al., 2008) (Wilbur Smith Associates et al., 2008)		(Gettman et al., 2008)	
Continuous Green-T		(Zawawa & Naghawi, 2019)	(Federal Highway Administration, 2016)	
Displaced Left-Turn intersection	(Bruce & Gruner, 2007) (Abdelrahman et al., 2020)	(Cheong et al., 2008)	(Inman, 2009) (Park & Rakha, 2010)	
Median U-Turn			(Jagannathan, 2007)	(El Esawey & Sayed, 2011) (Rahman et al., 2019)
Restricted Crossing U-Turn			(Kim et al., 2007) (Zhang & Kronprasert, 2013) (Federal Highway Administration, 2017)	
Diverging Diamond Interchange	(Federal Highway Administration, 2020) (Maji et al., 2013)	(Bared, Edara, et al., 2005) (Chlewicki, 2011)	(Claros et al., 2015)	(Siromaskul, 2010) (GWW, 2020) (Arcadis et. al., 2020)
Single-Point Urban Interchange		(Chlewicki, 2011)	(Bared, Powell, et al., 2005)	
NUUT-intersection				(Pan et al., 2020)

Literature shows that each country has their specific traffic rules, data, and travel behavior (AASHTO, 2018; CROW, 2013; El Esawey & Sayed, 2011; Rahman et al., 2010; Pan et al., 2020). If more countries are considered, then the workload and complexity of this study would significantly increase. Moreover, many scientific papers and information is available about the American variants and situations. For these reasons, the focus in this study is on American designs only.

2.2.3. American versus Dutch design standards

The United States uses the AASHTO guidelines, a policy on geometric design of highways and streets, to design their road network (AASHTO, 2018). According to the AASHTO, the design of each intersection should achieve an appropriate balance among the competing needs of pedestrians, bicyclists, motor vehicles, and transit with respect to safety, operational efficiency, convenience, ease, and comfort. Four basic elements should be considered in intersection design:

1. Human Factors; such as, behavior of road users, user expectancy, decision and reaction time
2. Traffic Considerations; such as, classification of each intersection roadway, existing and expected future crash frequency and severity, and size and operating characteristics of vehicles and modes
3. Physical Elements; such as, characteristics of the location, transit facilities, roadside design features, pedestrian cross walks, and traffic control devices.
4. Economic Factors; such as, the cost of improvements and the expected benefits

A similar approach is used in the Netherlands. The Dutch CROW guidelines and the ERBI (similar to the CROW guidelines but used by the province Noord-Holland) are based on the Sustainable Safety principles. Sustainable Safety is an initiative of various Dutch governments to increase road safety. Sustainably safe road traffic prevents fatalities, serious road injuries and permanent injuries by systematically reducing the underlying risks of the entire traffic system. By starting from the needs, competences, limitations and vulnerabilities of people, the traffic system can be developed in a realistic manner with maximum safety. The Sustainable Safety principles are described in section 2.3.2.

The approaches to make the roads safer from both countries are quite similar. However, there are some differences that must be noticed. For example, in the Netherlands, there is more focus on cyclists (and pedestrians), especially in urban areas. Cyclists usually have their own cycle lane on the road or share the same road with motorized vehicles without any form of separation. Therefore, speed limits tend to be lower in urban areas. At higher speeds, the cycle lanes are physically separated. The speed limits in the urban areas are restricted to at most 50 km/h (CROW, 2013). The lowest maximum speed limit can be found in certain street yards where the speed limit is 15 km/h. In most states of the United States a speed limit of 35 km/h yields for a similar situation, despite the presence of pedestrians, playing children, etc. (Federal Highway Administration, 2012).

In a study by El Esawey & Sayed (2011), a comparison of the traffic flow impacts is made between conventional and unconventional designs. No literature exists focusing on comparing the unconventional designs with European or Dutch designs. However, the conventional designs that are used in their study are similar to what is used in Europe and the Netherlands, with one major difference; all the designs are based on American design guidelines. Therefore, the dimensions of the roads differ between the two countries.

In a densely populated country like the Netherlands, the use of space must be taken into account. This is less important in the United States, where more space is often available. Because there is more space on the roads, American vehicles tend to be wider and longer as well. This is important to take into account when creating curves in roads as larger vehicles need more space.

All in all, it is shown that, despite the fact that the safety guidelines between the two countries are quite similar, infrastructural components in the United States cannot blindly be adopted in the Netherlands.

2.3. Studying the potential of unconventional designs in the Netherlands

When studying the potential of the unconventional designs to be used in the Netherlands, there are several topics to consider for the research. The focus of this research is mainly on geometrical/traffic engineering-related aspects. Other aspects, such as traffic psychology also play a role, as it is unknown how Dutch road users will experience such new designs. However, this type of research falls outside the scope of this study. This section of the literature review focuses on the following topics: The comparison between the American and Dutch guidelines for road design, ways to evaluate the traffic flow, and ways to evaluate the traffic safety.

2.3.1. Traffic flow evaluation

Traffic flow impact of unconventional designs

The same study by El Esawey & Sayed (2011), suggest potential capacity improvements and overall intersection delay reductions of Median U-Turns (MUT) compared to conventional intersections. Their results show through traffic model simulations that the conventional intersection with four legs reached its capacity at a volume of about 1295 veh/h, while the capacity of the MUT-design with signalized and unsignalized U-turns resulted in a capacity of 1425 and 1400 veh/h, respectively. This shows that the capacity increases with 8%-10%, compared to a conventional intersection, due to rerouting the left-turns.

Another study that demonstrates the benefits of unconventional designs is the study by Cheong et al., (2008), where three unconventional designs are compared in terms of average delays. Similar to the previously mentioned study, traffic models are built with the concerning designs. What all these unconventional designs have in common is that they reroute the left-turns. The results show that due to the rerouting of left-turns, all three designs outperform the conventional four-legged intersection in terms of average delays in various traffic conditions.

Microsimulation modelling

A way to get an indication of how the unconventional intersections and interchanges perform in Dutch conditions is by testing them through traffic models. Traffic models are models of road networks that are able to simulate how traffic propagates through the designed network. In other words, (part of) the physical reality can be represented. There are several factors that influence the determination of the traffic model. The factors are described below. What applied to this study, is mentioned in Chapter 3.

- type of goal that is being tried to achieve.
    - For example, to determine the traffic flow and traffic safety impacts.
- the demanded level of accuracy.
    - For example, if individual vehicle behavior is less relevant, then it can be chosen to build a macroscopic model instead.
- the available time, budget and resources.
    - Models with a high accuracy level require more time, and therefore, can be costly as well. This should be taken when considering the type of traffic model (microscopic/macroscopic).
    - The resources are related to the data.
- and the characteristics of the physical reality.
    - This also relates to the level of accuracy.

Therefore, the physical reality can be represented in different ways. Further, it must be noted that traffic models only represent a part of the reality. This means that the results of traffic models are only meant to give an indication of how a future scenario plays out.

Three popular microscopic traffic simulation packages that are available to be used are PARAMICS, VISSIM and SUMO. Other traffic simulation packages exist as well such as, AIMSUN, CORSIM, and TransModeller. However, due to the lack of availability, these software packages will not be considered for this study.

SUMO is non-commercial software. A key advantage of SUMO is that it takes account of different modes of transport, including pedestrians (Zambrano-Martinez et al., 2017). On the other hand, different types of vehicles are not taken into account, such as vans and trucks (Saidallah et al., 2016). Further, due to the complexity of the software, more time and effort is required to build a model, compared to other simulation software.

In PARAMICS, complex road networks (also, in 3D) can be modeled involving different modes and thus various type of road users. It must be noted that one of the major drawbacks of this software package is that not all road users, like pedestrians and cyclists, can be modelled visually. They can be taken into account when designing traffic light systems, however there is no input in the number of pedestrians or cyclists. As a result, interactions with motorized vehicles cannot be modeled. This drawback may affect the calibration and validation of the model.

Another popular software package is VISSIM. VISSIM is very similar to PARAMICS as it is also capable of modeling complex infrastructures in 3D with different entities propagating through this network. It can simulate various type of road users on the road and water (i.e., waterway traffic) (Higgs et al., 2011). This includes pedestrians and cyclists, as opposed to PARAMICS.

In addition to the simulations, traffic models also express the results quantitatively. When small networks are built, aspects like traffic flows and queues, can be shown with diagrams and graphs. With PARAMICS and VISSIM, their output can be used with SSAM. SSAM (Surrogate Safety Assessment Model) is a software tool to assess surrogate safety measures. Based on the results, statements can be made regarding the impact of the designs on traffic safety. Research from Essa and Sayed (2016) shows that both software packages show overall comparable results in terms of traffic safety when SSAM is used.

2.3.2. Traffic safety evaluation

According to El Esawey and Sayed (2013), there are four different approaches to evaluate traffic safety of unconventional intersections and interchanges. Each of these approaches is listed below. Several scientific papers that use one or more of these approaches to show the impact of unconventional designs on traffic safety are described as well. The four approaches are:

1. Conflict analysis;
2. Before-and-after analysis;
3. Driver confusion/perception analysis;
4. Simulation analysis.

Conflict analysis

Determining the number of conflict points is a quantitative and easy way to evaluate the traffic safety. Study by (Hughes et al., 2010) suggests that the unconventional interchanges and intersections that are covered by his study, have a lower number of unprotected conflict points. Theoretically, this means there is a lower potential for collisions and therefore are safer than conventional designs. The study by El Esawey & Sayed (2011), uses the same approach to determine the safety performance of a Median U-Turn.

Before-and-after analysis

This is the type of analysis where comparisons are made of a new situation where safety measures are taken, with the current situation. An example of this type of analysis is conducted by Jagannathan (2007), who performed a study to determine the traffic safety on a Median U-Turn intersection (MUT). Based on his study, he suggests that the number of collisions could possibly reduce by 20 to 50%, compared to a conventional intersection. The major safety benefit is a reduction in the probability of head-on and angle crashes that typically have high percentages of injury severity. Further, Hughes et al. (2010) suggests that the number of collisions on an unsignalized Restricted Crossing U-Turn (RCUT) reduces as well, compared to conventional solutions. In his case, a reduction was observed of 17% as an annual average of total crashes, and also a reduction of 41% as an annual average of severe crashes. In a similar study, where also the before-and-after analysis is used, shows reductions of 90% and 100% as an annual average of total and severe collision.

Not only do all these studies show that the before-and-after analysis is a great approach to evaluate the traffic safety, but they also prove that certain unconventional designs happen to improve the traffic safety, compared to conventional intersections.

Driver confusion/perception analysis

Especially with new, unconventional designs it is important that drivers know how to drive across the intersection or interchange. While driver confusion is a critical safety criterion, there are not many studies that focus on this regarding unconventional designs. As discussed before, the study by Shumaker et al., (2012) shows that familiarizing road users through proper education and experience, the public opinion on these unconventional designs improves.

Moreover, Inman (2009) conducted a study where driver confusion was being related to the used signings and road markings at a Displaced Left-Turn intersection (DLT). In this study, three different signing strategies were evaluated using a driving simulator. The results show, regardless of which signing strategy is used, none of the drivers were confused when they were confronted with the DLT for the first time. The author also suggests that the DLT has the potential to improve the traffic safety while maintaining a high capacity.

The studies show that driver confusion can be minimized several ways. This can be through familiarizing road users with the design, and by improving the recognizability of the design with road markings and signings. These aspects are taken into account by conducting a study regarding Sustainable Safety, also to determine to what extent the current, American designs already meet the Dutch design standards. More about the Sustainable Safety analysis is discussed later in another subsection.

Simulation analysis

The simulation analysis is in twofold. Traffic models can be simulated to determine the impact on traffic flow, as discussed in section 2.3.1. Scientific literature shows that the output of traffic models can be used with a Surrogate Safety Assessment Model (SSAM) to determine the impact on traffic safety. This modelling technique combines this output of the traffic models and automated conflict analysis to measure the traffic safety (Gettman et al. 2008). Study by Kim et al. (2007) used this approach with the SSAM to make a comparison regarding the traffic safety between a Restricted Crossing U-Turn (RCUT) and a conventional intersection. Two cases were analyzed; however, the results were mixed. In the first case, the RCUT appeared to reduce the number of conflicts by 80% compared to the conventional intersection. In the second case, the results were vice versa, and the number of identified conflicts appeared to be 80% higher for the RCUT.

Sustainable Safety analysis

The third safety evaluation approach is taken into account when conducting a Sustainable Safety analysis. As mentioned before, the crashes involving cyclists and motorized vehicles decreased due to the investments in safer infrastructure in the Netherlands. A way the road infrastructure is made safer is by designing them according to the Dutch CROW guidelines for road design. The guidelines are developed based on the concept Sustainable Safety.

If a traffic system complies with the Sustainable Safety principles, accidents are avoided as much as possible. If crashes cannot be prevented, then the probability that severe injuries occur is as low as possible. The principles are aimed at proactive measures in the field of, among other things, system design and traffic behavior. An evaluation study performed by Weijermars and Wegman (2011) discuss the effects of traffic safety measures that are based on Sustainable Safety principles. According to the study, it is estimated that all of the measures combined prevented 300 to 400 fatalities in 2007 and 1,600 to 1,700 fatalities between 1998 and 2007. Moreover, not only did the safety measures positively affect the traffic safety, based on a benefit-cost analysis, the measures appeared to be cost-effective as well.

The Sustainable Safety principles consist of five principles from which the first three focus on the road design:

1. Functionality of roads: among other things, related to whether the traffic system is meant to let traffic flow or to exchange traffic;
2. (Bio)mechanics: this is related to the homogenization of the traffic system and includes limiting the differences in speed, direction, mass and size, and giving road users appropriate protection;
3. Psychology: this is related to how well the traffic system is designed in a way that especially older road users are capable of recognizing how to safely participate in traffic. This means that even for them the information from the traffic system should be observable, self-explaining, credible, relevant and executable.

The remaining two principles are organizational principles, including: effectively allocating responsibility, and learning and innovating in the traffic system. These two principles do not focus on the geometrical design. Examples are monitoring speed and alcohol usage of drivers, and testing innovations in pilot areas.

2.4. Takeaways from the literature review

The literature review has shown that there are traffic-related issues in the Netherlands, where unconventional designs for intersections and interchanges could be seen as a possible solution to improve the traffic situations. Various studies abroad (and one in the Netherlands) indicate that unconventional designs improve the traffic flow and traffic safety, compared to traditional designs. Further, it is noticed that studies on how these innovative designs perform in the Netherlands are largely lacking. This is where this study can contribute.

Moreover, it is shown that through traffic models, various analyses can be performed to determine the impact of the designs on traffic flow and traffic safety. The two main analyses that are performed in this study are the conflict analysis and the simulation analysis, to evaluate both the traffic flow and traffic safety. Finally, the Dutch Sustainable Safety analysis is used to determine to what extent American (unconventional) designs comply to Dutch criteria for traffic safety and road design. This in turn results in the type of adjustments needed to build these designs in the Netherlands. The next chapter will show how these takeaways are used by converting it into a methodology for this study.

3
Research design

This chapter consists of two parts. First, the methodology of the research is described. Accordingly, the types of data analyses that are used are defined as well.

3.1. Methodology

Different methods are used in order to answer the sub questions. These are discussed below. The sub questions are mostly in the field of traffic engineering; however, the results of this thesis research could be used as a tool to create policies that will make it possible to realize such unconventional designs in the Netherlands.

1. *Based on theoretical advantages and disadvantages, which designs have the potential to be applied in the Netherlands?*

In Appendix A, a brief summary introduces a number of unconventional intersections and interchanges. The list of designs is reduced to two intersections and two interchanges for further research. This is done through a multi-criteria analysis, which is based on the theoretical advantages and disadvantages of each design. Subsequently, criteria are set up for a simple multi-criteria analysis. The criteria are determined based on the theoretical advantages and disadvantages which the reviewed literature (see, Table 6) focuses on. Based on this, the following criteria are used in the multi-criteria analysis: Traffic flow impact, traffic safety impact, technical feasibility, ease of use, use of space, and costs. Hereafter, scores are allocated to all the criteria. Each score is determined by the author of this study and motivated through desk research of scientific literature. This includes the advantages and disadvantages of each design as well. It must be noted that the criteria such as costs are not calculated. The reasoning for the scores is all based on the earlier found advantages and disadvantages. This is due to the fact that designs may differ depending on conditions in which it is used. This analysis is mainly meant to reduce the number of designs to a feasible amount for further research in the master's thesis.

The weight of each criterion is also determined by the author of this study. It is chosen to make the traffic flow impact and traffic safety impact criteria weigh twice as much as the rest. This is because the main research question focuses on these two criteria.

Additionally, a workshop is held at the province Noord-Holland. The main purpose of this workshop regarding this sub question is to receive expert judgement on the chosen designs, after being presented. The designs already show through scientific literature that they have the potential for further research; however, the experts could have had differed in opinions. Thus, the purpose is to determine the potential of these chosen innovative designs on the Dutch (provincial) roads, based on their opinions. This can be interpreted as an extra justification on the chosen designs. Responses of the experts and professionals are monitored by using Mentimeter. This way, the workshop is made interactive.

2. *If these structures were to be built in the Netherlands, the way they are in the United States, what are the necessary modifications to meet the Dutch criteria for traffic safety and road design guidelines?*

In Section 2.2.1 and 2.3.2, it is shown that the safety approaches from the Netherlands and the United States are quite similar. However, it is also indicated that the American designs cannot blindly be adopted in the Netherlands. Even though similar principles are held to in both countries, the roads in both the Netherlands and the United States are composed of different types and volumes of traffic. Sizes and speeds of vehicles differ as well. For this reason, it is checked to what extent currently built unconventional designs in the United States comply with the Dutch Sustainable Safety principles.

Sustainable Safety principles (SWOV, 2018a) by the Dutch Institute for Road Safety Research are used, along with the Dutch and American guidelines for road design (CROW, 2013; AASHTO, 2018). This is based on the desk research conducted for the previous sub questions. Sustainable Safety principles focus on designing the traffic environment in such a way that no serious accidents can occur. If an accident does occur, then severe outcomes remain limited.

The main focus is on the first three (design) principles only. The remaining two principles are organizational principles and fall outside the scope of this research. Accordingly, the last two principles are not taken into account in this research.

A desk investigation is constructed according to the three design principles. For this desk investigation, criteria of the Sustainable Safety principles are rephrased to questions which only the author of this study gave answer to for each of the designs, based on observations made through Google Maps/Street View. For instance, the first principle is regarding the functionality of the road. Based on the road characteristics, questions are asked to determine the functionality of the roads that form the intersection/interchange. This in turn determines the road categorization. A similar approach is done for the other design principles as well. Lastly, the Dutch and American guidelines for road design (CROW, 2013; AASHTO, 2018) are also used to determine more in detail the exact adjustments that are necessary.

3. *What are the steps that need to be taken in order to introduce such new designs to the Dutch roads?*

Earlier for sub question 1, one of the purposes of the workshop held at the province Noord-Holland was described. However, another purpose of the workshop is to get an answer on the third sub question. This sub question was asked as a follow-up question when one of the chosen designs was rated positively for further research. Their answers are used as a guide to answer this sub question.

4. *What is the impact of the selected designs on the traffic flow, traffic safety, and on its surroundings under Dutch circumstances?*

Several studies in Section 2.3.1 show that unconventional designs improve the operational performance compared to conventional intersections, and thus, show potential for further research. The impact of these designs on traffic flow, traffic safety, and its surroundings are determined by building traffic models under Dutch circumstances. There are several factors that influenced the determination of the traffic models. These were briefly described in the literature review (see, Chapter 2). The factors are mentioned below, including what applied to this study:

- type of goal that is being tried to achieve;
    - In this case, the goal was to determine the traffic flow and traffic safety impacts.
- the demanded level of accuracy;
    - For example, if individual vehicle behavior is less relevant, then it can be chosen to build a macroscopic model instead. However, for this study a higher level of accuracy was preferred as various road users like cyclists and pedestrians are taken into account as well.
- the available time, budget and resources;
    - Models with a high accuracy level require more time. This should be taken when considering the type of traffic model (microscopic/macroscopic). Since a microscopic approach was chosen, only a small number of intersections/interchanges were designed. This was already taken into account.
    - Budget was not relevant in this case.
    - The resources are related to the data. Data was provided by the province. This included traffic volumes and cycle times of traffic signals. The provided data was not complete. In those cases, hypothetical values were used. These are indicated in Chapter 6.
- and the characteristics of the physical reality.
    - This also relates to the level of accuracy.

When building the traffic models, the first step was to determine where in the Netherlands these designs could be built. The province Noord-Holland owns all the N-roads within the province and also has the required data related to these roads. This data (traffic volumes and signal schemes) is necessary to build the traffic models. One location is chosen where its intersection can be replaced by all intersection designs, and another location where its interchange can be replaced by all the interchange designs. The characteristics of the locations and the designs played a role in choosing the locations. Aspects such as the number of connections of the current intersection/interchange, the amount of space, and the presence of slow traffic and public transport were considered when choosing the locations.

In Section 2.3.1 three popular microscopic simulation software packages are discussed. Due to complexity, SUMO was not preferred to be used for this research. Since PARAMICS and VISSIM are microscopic software packages, they serve the same purpose. A similar type of output is being generated. Both their output can be used to determine the impact of the designs on traffic flow and traffic safety. Only several small differences exist between both packages that are relevant for this study. An example in favor of VISSIM is that it visually simulates pedestrians and cyclists. However, they are being taken into account in PARAMICS when creating traffic signals. An example in favor of PARAMICS is that modifying traffic signals to turn them into vehicle-actuated signals, requires less time and effort due to its simplicity and the required syntax is known. Moreover, both software packages have been used before and from a personal point of view, building a model in PARAMICS is more straightforward. All in all, the decision between two majorly came down to personal experience as both packages provide all the necessary output for this study. Due to having more experience with PARAMICS, this software package was chosen to be used. To take account of pedestrians and cyclists, only signalized intersections and interchanges are modelled.

The traffic models consist of small networks where the current (reference) locations are built. To keep the amount of work with the models feasible, only the morning peak hours are simulated. Two hours are simulated, where the first hour is meant to make the traffic get used to the infrastructure. The second hour is more representative and is used for the data analysis. The simulation does not end with an empty network. This means that no demand profiles are assigned that can vary the demand of traffic within a simulated hour.

When the current situation was built, the existing intersection/interchange was then replaced by the earlier chosen unconventional designs and simulated as well. The intersection designs are built at the locations where an intersection is located, while the interchange designs are built at the location where an interchange is located. On certain locations, green waves are necessary when multiple intersections are present in the road network. Due to the complexity of applying green waves into the model, a more pragmatic approach was chosen by turning the fixed signals into vehicle-actuated signals. With the use of detectors, the model can decide whether to give extra green time during a phase. If it is necessary, then the maximum green time is used. Otherwise, the traffic flows according to the minimal green time in that phase. The distance between a detector and an intersection matter. When the distance is large, it means that the lane allows to have a relatively large queue. When the detector is placed closer to the intersection, it means that the detector will be activated with shorter queues. As a result, the maximum green time is given more often.

After all the traffic models were built, a qualitative estimation is made on how the designs impact the surroundings of the locations where the designs are being used. This is related to aspects such as use of space, possible detours, and involved types of road users. Further, data is extracted and used for analysis regarding the impact of the designs on the traffic flow and traffic safety. With Excel, the traffic flow data was easily converted into graphs. The traffic safety data, however, required more effort. Through Excel, it was only possible to determine rear-end conflicts. Reference is made to the next section regarding data analysis where the performance and safety indicators/measures are explained. Accordingly, the way the results are extracted from the data is explained as well.

An overview of the methodology is depicted in Figure 2. An enlarged version is provided in Appendix B.

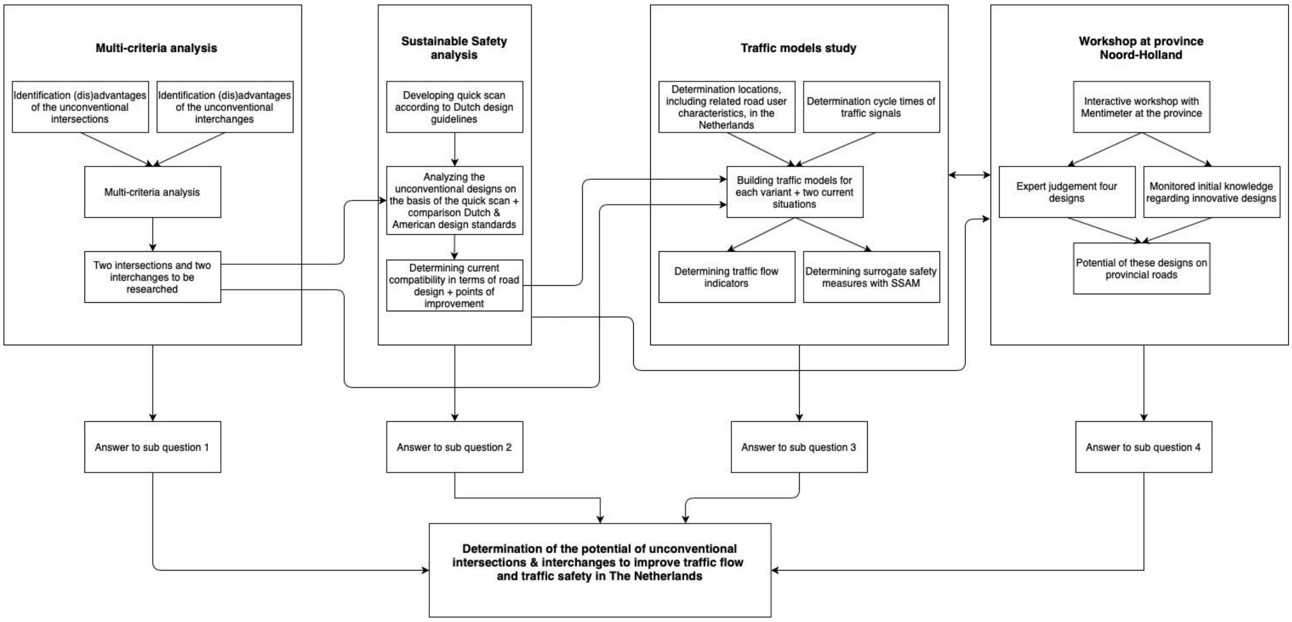

Figure 2 Overview methodology

3.2. Data analysis

The data analysis is in threefold. Firstly, the workshop held at the province Noord-Holland was, among others, used to gain insight in how people of the province think of such concepts, as they have a different working method at the province. Furthermore, to discuss two cases where these designs could be built, to receive expert judgement regarding these designs. Lastly, the workshop will also be used to gain additional knowledge which can complement the rest of this research, such as topics that were not considered in this study, prior to this workshop.

Secondly, the desk investigation based on Sustainable Safety principles can give an impression of how well the unconventional designs comply with the Dutch design principles. The desk investigations result in qualitative information. If the results reveal that too many modifications are necessary, certain alternatives can be disregarded for further research in this study.

Furthermore, traffic models are modelled and simulated. The performance indicators and surrogate safety measures that are calculated are explained below. Motivations for choosing these indicators and measures are mentioned in Sections 6.4 and 6.5.

Table 7 Overview of the performance indicators and safety measures

Traffic flow performance indicators	Surrogate safety measures
Travel times (all trips) A reduction of the travel times of all trips would indicate that the overall traffic flow improves at the location.	**Time-To-Collision (TTC)** This indicates the time-to-collision during the conflict. Lower values indicate a higher chance to accidents.
Travel time differences By subtracting the travel times of the alternatives from the current (reference) situation, the difference in travel times is determined.	**Post-Encroachment-Time (PET)** This is the time between when the first vehicle last occupied a position, and the second vehicle's arrival at that same position. The PET value represents the extent to which the two vehicles

	missed each other. A collision is indicated by a value of zero.
Vehicle counts This indicates the number of vehicles per period in the network. Dependent on the “Travel time (all trips)” indicator, a statement can be made regarding the results for the counts. For example, when there are more vehicles present with an alternative, compared to the current (reference) situation, it could either mean that the capacity increases with the alternative, or that traffic flow performs less efficient compared to the current (reference) situation. Thus, if the counts indicate that there are more vehicles present, and the “Travel times (all trips)” indicator shows a reduction in travel time, then it will mean that the capacity increases with the alternative.	**Deceleration rate (MaxD)** The deceleration of the second vehicle (negative value when decelerating. If positive, then the vehicle did not decelerate).
Average distance travelled In certain designs, left-turns are being rerouted, possibly increasing the distances travelled by vehicles at the location. Dependent on how significant the differences in travelled distances are between the current (reference) situation and with an alternative design, a statement can be made regarding the effects of the rerouting on its impact on traffic flow.	**Speed differentials (DeltaS)** Difference in speeds between consecutive vehicles. It is desired to have differences in speed as low as possible. This in turn contributes to an improved traffic safety (SWOV, 2018a).
	Conflict types The number of conflict points (locations on the intersection/interchange where the paths of road users intersect) can schematically be depicted. In this study, the vehicle-vehicle conflict types are classified in three categories: crossing, merging, or diverging conflict points. Additionally, the vehicle-cyclist/pedestrian conflict points are taken into account as well. Generally, the crossing conflict points, where vehicles are moving in different directions, are associated with more severe crashes than the other two mentioned conflict types. Despite the fact that a distinction in severity can be made between the conflict types, the extent to how severe potential conflicts are cannot be determined only by this safety measure. Fortunately, the other four safety measures help determining the extent of severity.

PARAMICS is used to determine the traffic flow impacts of the designs. The data output can then be used in Excel to create the necessary graphs to make mutual comparisons and eventually a statement regarding the impacts on traffic flow.

The impact on traffic safety is determined with other data output of PARAMICS and require more effort to obtain the right information. Through Excel, it is only possible to determine rear-end conflicts. The vehicle data consists of the vehicle positions, accelerations, speeds, and timestamp. The procedure to get results for the safety measures is explained below.

Table 8 Procedure to determine results the surrogate safety measures

Surrogate safety measure	Procedure to obtain results
Time-To-Collision (TTC)	TTC is calculated in two ways: $$\frac{\Delta X}{\Delta V}\ or\ \frac{\Delta Y}{\Delta V}$$ To know which formula to take, it has to be checked how the vehicles drive on the location. There are two roads crossing each other. If the links (road sections) are more horizontally dimensioned, then the formula with ΔX is used to take account of rear-end collisions. When the links are dimensioned more vertically, the formula with $\Delta Y$is used. Before using this formula, the data is sorted consecutively by link, timestamp, X-coordinates, and Y-coordinates (or X). Hereafter, the formulas for TTC are used. Then the results for the X-, and Y-coordinates are added up. Finally, the threshold value is used to filter out the data to only show the values that are smaller than the predetermined threshold value. Which threshold value are used is discussed in the corresponding Chapter 6. The remaining data shows the number of severe rear-end conflicts, based on TTC.
Post-Encroachment-Time (PET)	PET is determined by first by sorting the data on the links, then the X-coordination (or Y), then the Y-coordinates (or X), then the timestamp. Then the absolute PET value is calculated for consecutive vehicles. $$PET = \Delta t_{1,2}$$ Hereafter, the results are depicted in a graph. PET-values between 0.0 and 5.0 are divided to get a better indication in the near misses and actual

	accidents. Here, a value of 0.0 indicates an actual accident. Any PET value higher than 5.0 has an insignificant chance for collisions, thus no further distinction is made after 5.0.
Deceleration rate (MaxD)	Accelerations of each vehicle is part of the output of PARAMICS. To get the decelerations, the data is filtered to only show the negative accelerations (i.e., decelerations).
Speed differentials (DeltaS)	Speeds of each vehicle is part of the output of PARAMICS. The difference between the speeds of consecutive vehicles is then calculated.
Conflict types	These are not obtained through the PARAMICS data. See, Table 7 for further explanation.

4
Identifying potential designs for further research

In the literature review, a total of ten designs consisting of American unconventional intersections and interchanges were analyzed. In this chapter, the advantages and disadvantages of each design are considered to reduce the number of alternatives to a feasible amount for further research in this study. This is done with a multi-criteria analysis. The number of designs is accordingly reduced to two intersections and two interchanges.

The remaining of this chapter start with the multi-criteria analysis in Section 4.1, including a description of the criteria that are used, and the allocated scores. Hereafter, the results of the multi-criteria analysis are presented, along with a description of each chosen design. Finally, this chapter ends with a conclusion, answering the first sub question.

4.1. Multi-criteria analysis

In Appendix A the ten unconventional designs are compared based on several criteria, according to their advantages and disadvantages. The intersection designs are compared to a conventional four-legged intersection, while the interchanges are compared to a conventional diamond interchange. It must be noted that the comparisons are all rough estimates. This is due to the fact that designs may differ depending on conditions in which it is used. Each score is determined by the author of this study and motivated through desk research of scientific literature. This analysis is mainly meant to reduce the number of designs to a feasible amount for further research in this report. All the scores, including the weight factors, are fully determined by the author of this research.

4.1.1. Criteria

The criteria used in the multi-criteria analysis is briefly described below. These are determined based on the theoretical advantages and disadvantages which the reviewed literature (see, Table 6) focuses on. Based on this, the following criteria are used in the multi-criteria analysis: Traffic flow impact, traffic safety impact, technical feasibility, ease of use, and costs.

The alternatives can score points on a 5-point scale, with 1 meaning a very negative effect, while 5 is very positive. 3 points imply that no significant differences are to be expected. Moreover, matching colors are used for an additional clarity in the form of a heat map. In other words, red (very negative) means 1 point is allocated, while green (very positive) means that 5 points are allocated. Similarly, the remaining colors orange, yellow and light green indicate 2, 3 and 4 points, respectively. If available, references are made to scientific literature for additional motivations of the allocated scores.

Table 9 Explanation Multi-criteria analysis criteria

Criterion	Description
Traffic flow impact	The traffic flow impact is not calculated. The impact is estimated based the infrastructural characteristics, such as how the design works, the number of required intersections, and whether the design is at-grade or grade-separated. Also, the reported benefits play a role in the estimation process. These were described before in Appendix A.
Traffic safety impact	Several sub criteria determine the traffic safety impact. These are: the approximate degree of confusion which the design may cause to the driver, and the presence of facilities for (crossing) pedestrians and cyclists. Also, the number of conflicts give an indication about the traffic safety.
Technical feasibility	This criterion focuses on the complexity of the design and the degree of reconstructions required for a current situation. When designs are too complex, it is possible that it brings more difficulty to create policies allowing such designs in the Netherlands. Preferably this is not desired. In this case, 5 points mean that the design can be built where the Dutch design guidelines form no obstruction. 1 point indicates that the design is very complex and consists of components that need to undergo a process in order to be implemented in the Dutch design guidelines.
Ease of use	The complexity to use intersection or interchange is also important. Aspects such as the number and length of redirections play a role in determining the score of this criterium. This also applies to pedestrians and cyclists. In this case, 5 points mean that the design would not cause any confusion among road users and is therefore comparable to a conventional intersection. While 1 point indicates that the design is complex and as a result can cause confusion.
Use of space	The use of space assessed in terms of compactness. In densely populated countries such as the Netherlands, it might not be feasible to construct large designs on many occasions. Therefore, the compactness of designs is important.
Costs	This is related to the size of the structure. The use of space plays a role as well. Obviously, large constructions will score poorly on this criterion. Also, this is only an estimation; the exact costs are not calculated.

4.1.2. Scores MCA

The scores per criterion are indicated per design. The weights from the previous subsection are also filled in. As mentioned before, each score is determined by the author of this study and motivated through desk research of scientific literature. The results are shown in the two tables below. Reference is made to Appendix D for the motivation behind each score.

Table 10 Comparisons unconventional intersection designs with respect to a conventional four-legged intersection

Intersections	Traffic flow impact	Traffic safety impact	Technical feasibility	Ease of use	Use of space	Costs	Total score
Weights	2	2	1	1	1	1	
Center Turn Overpass	5	4	1	5	5	1	30
Continuous Green-T	4	3	2	2	2	2	22
Displaced Left-Turn Intersection	5	2	3	3	2	4	26
Echelon	5	2	1	4	5	1	25
Median U-Turn	4	5	4	4	4	4	34
Quadrant Roadway	4	4	4	3	5	5	33
Restricted Crossing U-Turn	4	5	4	3	4	4	33

Table 11 Comparisons unconventional interchange designs with respect to a conventional diamond interchange

Interchanges	Traffic flow impact	Traffic safety impact	Technical feasibility	Ease of use	Use of space	Costs	Total score
Weight	2	2	1	1	1	1	
Displaced Left-Turn Interchange	5	2	3	3	1	1	22
Diverging Diamond Interchange	4	5	4	3	4	5	34
Single-Point Urban Interchange	5	4	3	4	3	2	30

4.1.3. Results

In case of the interchanges, the Displaced Left-Turn (DLT) interchange scores the worst for most criteria. It only scores well regarding its traffic flow impact. Initially, it was decided to choose two intersections and two interchanges for further research. Regardless of which weights you use, the DLT interchange will never score better than the other two. This way, the two interchanges are already chosen. Moreover, both the remaining alternatives do score well on most criteria. Therefore, the potential is shown for further research.

When looking at the designs that score over 30 points, the Center Turn Overpass is disregarded as the costs are too high. Moreover, the Median U-Turn (MUT) and the Restricted Crossing U-Turn (RCUT) are quite similar designs. Due to the similarities, it was considered more convenient to only pick one of them. In this case, the Median U-Turn was chosen for further research as it scored slightly better. The idea for this study was, given the MUT being for further research, to do a research on only the MUT from these similar designs. If it turned out that the MUT had potential to be implemented in the Netherlands, the chances would be high that it would also apply for the RCUT. Then, this similar design would be mentioned for further research in the Recommendations section. Lastly, the Quadrant Roadway, was chosen as well. This alternative scores well, especially in terms of space usage and costs.

The designs that are chosen for further research are covered in the next section. For the complete list of all the designs, reference is made to Appendix A. The pictures and general descriptions all come from the Virginia Department of Transportation (2021) website. The advantages and disadvantages are deduced from the quality assured report from Hughes et al. (2010) and a report by Wilbur Smith Associates et al. (2008), unless indicated otherwise.

4.2. Intersections

Median U-Turn

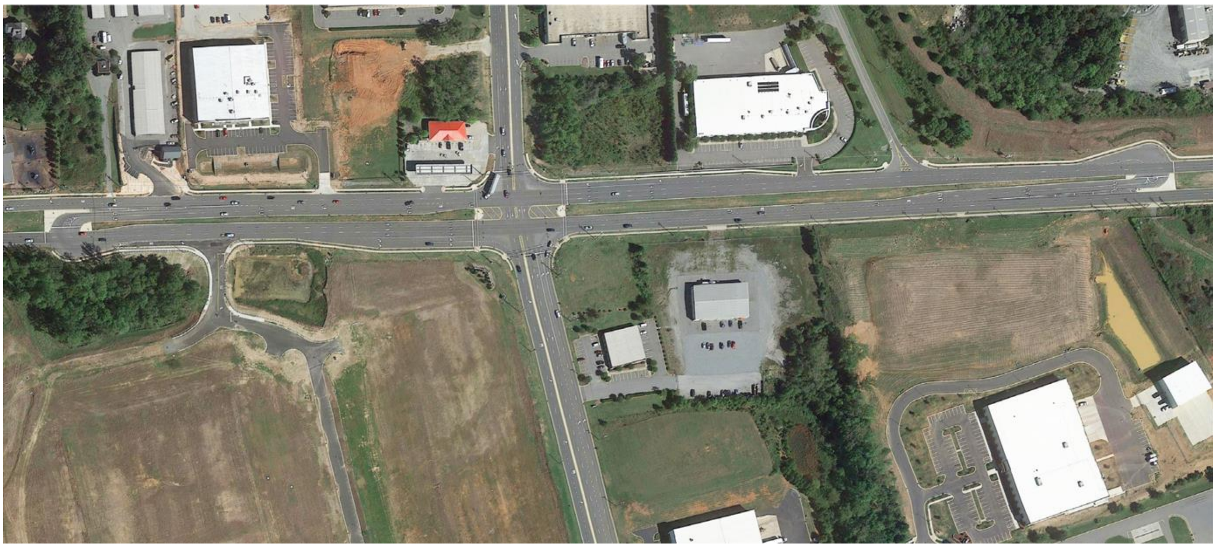

Figure 3 Poplar Tent Road at Derita Road, Concord, N.C.

The Median U-Turn (MUT) is made up of one main intersection and two median crossover intersections. All left-turns are completed by making a U-turn by one of the median crossovers. Traffic that wishes to go straight ahead or turn right proceed as they would on conventional intersections. It is also possible to use roundabouts instead of U-turns. In that case the intersection is called a Bowtie. The MUT can be designed as signalized, stop controlled, or yield controlled. This design can be considered in urban and suburban areas and is suitable under conditions with moderate to heavy through-traffic volumes on the main road and low to moderate left-turn traffic volumes from all approaches. The MUT has 16 conflict points, consisting of 4 crossing, 6 merging, and 6 diverging conflict points. On the other hand, a conventional intersection has 32 conflict points, consisting of 16 crossing, 8 merging, and 8 diverging conflict points. The vehicular movements on this type of intersection are illustrated below.

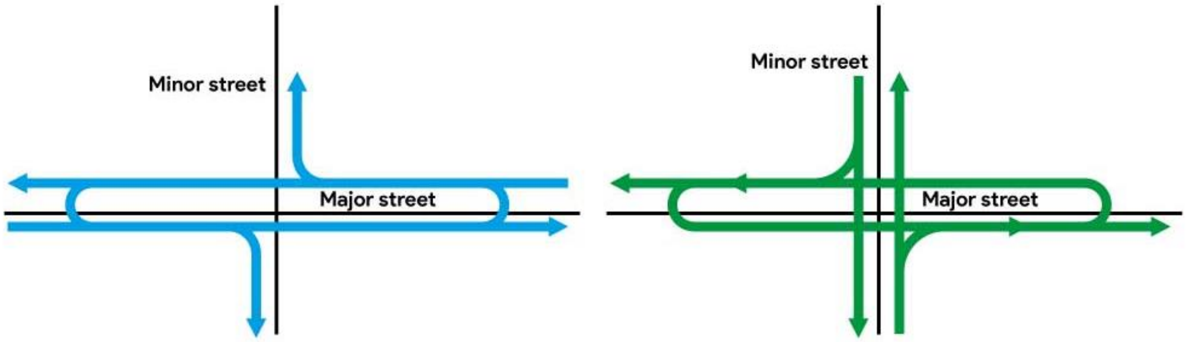

Figure 4 Vehicular movements on a Median U-Turn. Left: major street movements. Right: minor street movements

Advantages (Wilbur Smith Associates et al., 2008)

- By prohibiting left-turns at the main intersection, the initial signal with four phases is reduced to only two.
- With only two phases, the road capacity increases.
- Dependent on the development in its vicinity, the constructional costs are relatively low.
- Overall reduction in crashes (Federal Highway Administration, McLean, VA. 34, 2007)
- The number of crossing conflict points reduces by half, indicating a positive impact on traffic safety.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- Compared to a conventional intersection, it can become less efficient if there are heavy volumes of left-turn and through going traffic from the side streets.
- New intersection with U-turns is something new. Drivers have to get used to the unconventional intersection.
- It is possible that too much weaving is involved between the main intersection and a U-Turn.

Quadrant Roadway

Figure 5 State Route 4 at State Route 4 Bypass/Ross Road, Fairfield, Ohio.

The Quadrant Roadway (QR) is a type of intersection consisting of one main intersection and two secondary intersections that are connected with a connector road in any quadrant of the intersection. Vehicles wanting to make a left-turn at the main intersection are rerouted with the connector road, to complete the left-turn movements. In which quadrant the connector road should be implemented depends on the left-turn demand. Typically, the direction with the highest left-turn demand uses the most direct route, while the longer route is allocated to the direction with the lowest demand. The secondary intersections are signalized but can also be designed without any signals, thus stop or yield controlled. When all three intersections are signalized, traffic signals are synchronized in a way to create a green wave. This design can be considered in urban and suburban areas when heavy through and left-turning traffic volumes are present in all directions. Below, the left-turn movements from two approaches are shown. The QR has 30 conflict points, consisting of 10 crossing, 10 merging, and 10 diverging conflict points. On the other hand, a conventional intersection has 32 conflict points, consisting of 16 crossing, 8 merging, and 8 diverging conflict points.

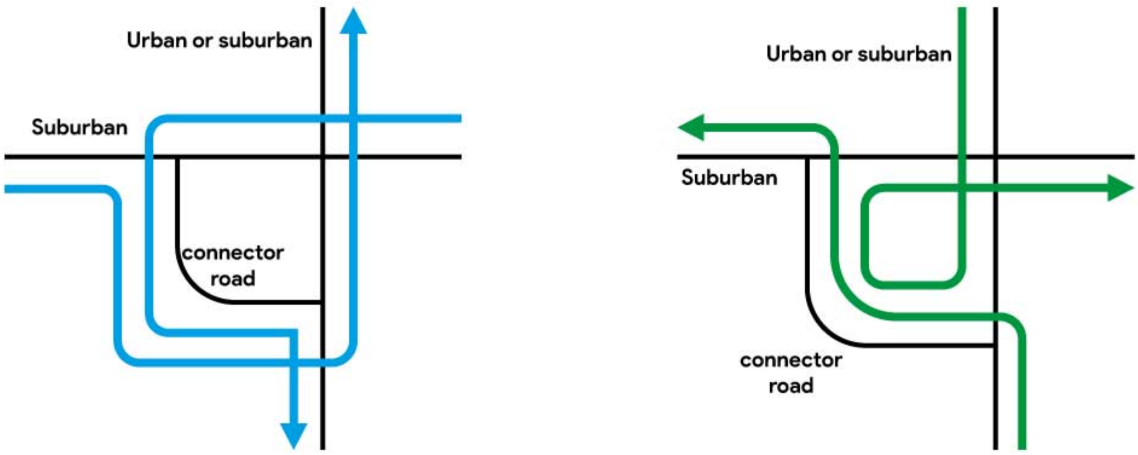

Figure 6 Vehicular movements on a Quadrant Roadway from two different approaches

Advantages

- The intersection can also be implemented as an adjustment to existing infrastructure, where existing streets could function as the connector road. However, it must be taken into account that the road capacity is sufficient. If all of this is the case, a very cost-efficient intersection is created.
- From a geometric perspective, it is relatively easy to design and implement.
- The signalized main intersection requires only two phases when all left turns are prohibited. Simultaneously, this results in three phases on the signalized secondary intersections. In other words, the traffic flow improves.
- The traffic light system can be synchronized in a way to create a green wave. This way the motorized vehicles do not have to stop at every intersection.
- The number of conflict points is spread out from one intersection to three and is slightly reduced.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- If all left-turns are prohibited it means that these will all use the connector road. Therefore, a sufficient road capacity and traffic flow is necessary.
- Prohibiting left-turns may be quite unusual. This is something that road users have to get used to.
- The synchronized traffic light system is relatively complex to design. Besides the green wave for motorized vehicles, the pedestrians and cyclists need a sufficient amount of time to cross the road.
- The number of conflict points might be spread out, but the number of intersections increase.

4.3. Interchanges

Diverging Diamond Interchange

Figure 7 I-64 at U.S. 15 (James Madison Hwy), Zion Crossroads, Va.

The Diverging Diamond Interchange (DDI) is a grade-separated interchange where traffic from the suburban road navigates between the freeway ramps. Vehicles that want to make left-turns first move to the left side of the road between the ramps. As a result, it allows them to continue driving towards the on-ramps without conflicting with the opposing through traffic.

The right-turns on and off the ramps occur either before or after the crossover intersections, which is clearly depicted in the illustration below. Furthermore, both crossover intersections are signalized, and the intersections can be designed as an overpass or underpass. This design can be considered in suburban areas with heavy left-turning traffic volumes entering/exiting the freeway ramps. The DDI has 18 conflict points, consisting of 2 crossing, 8 merging, and 8 diverging conflict points. Contrarily, a conventional diamond interchange has 22 conflict points, consisting of 6 crossing, 8 merging, and 8 diverging conflict points.

The illustration below shows the vehicular movements on a DDI. The colors green and blue indicate the movements of through traffic on the side street, each from a different approach. Red indicates the on and off ramps.

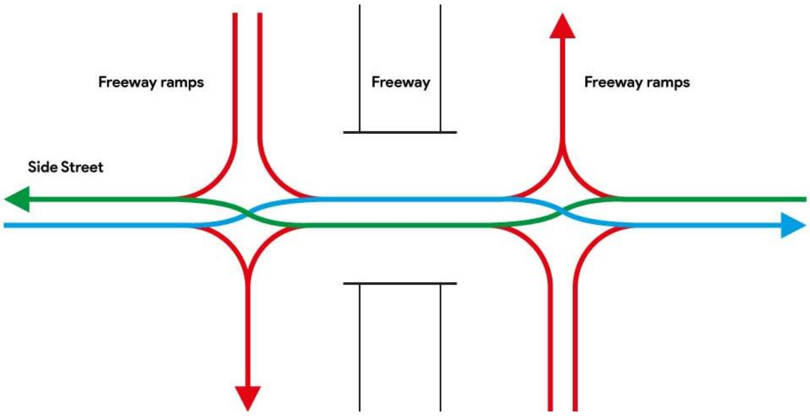

Figure 8 Vehicular movements on a Diverging Diamond Interchange

Advantages

- It improves the traffic flow in cases of high demand of left-turns and through going traffic.
- The signalized intersections require only two phases.
- The design ensures that there are less conflict points, improving the traffic safety compared to a conventional diamond interchange.
- Smaller footprint; Requires less lanes, compared to other interchanges that handle the same amount of traffic.
- Offers constructional cost benefits, compared to other interchanges that handle the same amount of traffic.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- The design is quite unusual as it gives the impression that drivers get to drive on the wrong side of the road. This is something that road users have to get used to.
- Multiple crossings are necessary when pedestrians and cyclists are involved.

Single-Point Urban Interchange

Figure 9 U.S. 50 (Arlington Boulevard) at Gallows Road, Falls Church, Va.

The Single-Point Urban Interchange (SPUI) is a variant of the conventional diamond interchange, where the two intersections have moved to the center, forming a single intersection. All the ramps begin or end at this signalized intersection on the suburban road. The right-turns on and off the ramps occur on bypasses to reduce the load on the main intersection. The intersection platform can be designed as an overpass or underpass. Further, this design can be considered in urban and suburban areas with heavy left-turning traffic volumes entering/exiting the freeway ramps. The SPUI has 24 conflict points, consisting of 8 crossing, 8 merging, and 8 diverging conflict points. On the other hand, a conventional diamond interchange has 22 conflict points, consisting of 6 crossing, 8 merging, and 8 diverging conflict points.

The illustration on the right shows a SPUI interchange with the vehicular movements and directions. Blue is indicating the vehicular movements originating from the freeway ramps, while red indicates the traffic from the side street. Further, yellow indicates the through going traffic on the side streets. Lastly, green indicates all right turns.

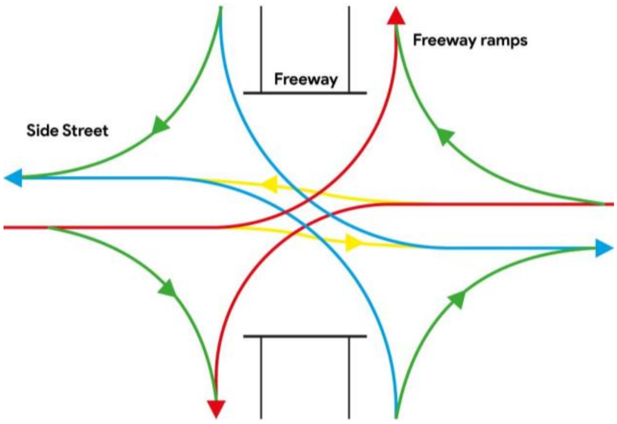

Figure 10 Vehicular movements on a Single-Point Urban Interchange

Advantages

- Improved traffic flow and road capacity.
- The signalized main intersection requires three phases.
- Improved traffic safety, as vehicles only have to cross one intersection, instead of two at a conventional diamond interchange.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- Relatively higher costs compared to a conventional diamond interchange.
- Longer clearance times due to the large intersection.
- Adding pedestrian crossings and cycle lanes is possible but less convenient compared to a conventional intersection.

4.4. Conclusion

A total of ten unconventional designs consisting of intersections and interchanges were analyzed to answer the first sub question of this research. This question was as follows:

Based on theoretical advantages and disadvantages, which designs have the potential to be applied in the Netherlands?

The advantages and disadvantages were weighted up through a multi-criteria analysis, resulting in two intersections and two interchanges which are used for further research in this report. Examples why a certain design is not chosen are due to the lack of benefits, significantly high costs, or when it is too similar to another design that is already chosen. The following designs are chosen:

1. Median U-turn
2. Quadrant Roadway
3. Diverging Diamond Interchange
4. Single-Point Urban Interchange

These are the four designs that are analyzed regarding their impact on traffic flow and traffic safety under Dutch conditions.

5
Sustainable Safety evaluation leading to necessary modifications

In Section 2.2.3 it was explained that the United States uses the AASHTO guidelines to design their roads. These guidelines also include elements regarding the traffic safety at intersections. In the Netherlands, CROW guidelines are commonly used (while the ERBI by the province Noord-Holland) to design the Dutch roads. In this case, the Dutch guidelines are based on the Sustainable Safety principles, which aims to develop the traffic system with maximum safety.

It was shown that the safety approaches from both countries are quite similar. However, it is also indicated that the American designs cannot blindly be adopted in the Netherlands. Even though similar principles are held to in both countries, the roads in both the Netherlands and the United States are composed of different types and volumes of traffic. Sizes and speeds of vehicles differ as well. For this reason, it is checked to what extent currently built unconventional designs in the United States comply with the Dutch Sustainable Safety principles. Based on this it can be concluded whether certain modifications are necessary in order to use such designs in the Netherlands. Although the Sustainable Safety principles do not focus on certain specific infrastructural components, such as U-Turns, it may ease the process to consider such designs to be implemented in the Dutch guidelines for road design.

Based on the multi-criteria analysis, four designs were chosen for further research. As most of these designs have never been built before in the Netherlands, four locations in the United States are chosen where the analysis is performed. Accordingly, Sustainable Safety principles are used, in combination with the Dutch and American design guidelines. Sustainable Safety principles focus on designing the traffic environment in such a way that no serious accidents can occur. If an accident does occur, then severe outcomes remain limited (SWOV, 2018a). A desk investigation is constructed using the Sustainable Safety principles and the design guidelines. For this desk investigation, criteria of the Sustainable Safety principles are rephrased to questions which only the author of this study has given answer to for each of the designs, based on observations made through Google Maps/Street View. Through the desk investigations, the traffic safety is evaluated, and the necessary modifications are determined.

Reference is made to Section 2.3.2, where the Sustainable Safety principles and this type of analysis is explained in detail.

In Section 5.1, the locations are described where these four unconventional designs are present. Hereafter, in Section 5.2, theoretical aspects of the desk investigation are discussed. Section 5.3presents the results from the desk investigation. Finally, conclusions are drawn in Section 5.4, answering the second sub question.

5.1. Locations

The same locations are chosen that are depicted in the pictures used in the previous chapter. These are:

1. Median U-Turn ➔ Poplar Tent Road at Derita Road, Concord, N.C.
2. Quadrant Roadway ➔ State Route 4 at State Route 4 Bypass/Ross Road, Fairfield, Ohio.
3. Diverging Diamond Interchange ➔ I-64 at U.S. 15 (James Madison Hwy), Zion Crossroads, Va.
4. Single-Point Urban Interchange ➔ U.S. 50 (Arlington Boulevard) at Gallows Road, Falls Church, Va.

The desk investigation will determine the differences in how traffic safety is taken into account in the design. However, it must be noted that each location might have certain characteristics that are location-bound, for example small sidewalks due to lack of space. Therefore, the possibility is there that these characteristics are not present on locations in the Netherlands where these designs could get used. Nonetheless, the assumption is made that similar locations exist in the Netherlands. Even if certain characteristics are location-bound, the results will show when such compromises in the traffic system are present, how it will influence traffic safety.

5.2. Desk investigation Sustainable Safety

As discussed in the literature review, Sustainable Safety principles consist of five principles from which the first three focus on the road design (SWOV, 2018a). These are also briefly discussed below.

As mentioned before, the four designs are assess based on the Sustainable Safety principles, where these principles were rephrased to questions. For instance, the first principle is regarding the functionality of the road. Based on the road characteristics, questions were asked to determine the functionality of the roads that form the intersection/interchange. This in turn determines the road categorization. A similar approach was done for the other design principles as well. For questions related to the geometry of the design, the Dutch (CROW, 2013) and American (AASHTO, 2018) road design manuals were used for the verification purposes. The answers on the questions were used to evaluate the traffic safety and determine the necessary modifications to use these designs in the Netherlands. If necessary, pictures from Google Maps/Street View were used as well in the desk investigations for additional clarifications of certain aspects. Reference is made to Appendix D for the desk investigation.

5.2.1. Functionality

In an ideal situation, road sections and intersections only have one function in traffic. Traffic can either flow freely without being obstructed by other directions (such as, on highways and junctions) or traffic has to be exchanged (i.e., traffic can move from one road, to an intersection road), This is also called the mono functionality. These functions form a hierarchical structure in the Dutch road network. The hierarchy in the road network is necessary for the purpose of traffic safety. For example, you cannot have pedestrians and cyclists on freeways due to the high vehicle speeds.

In certain occasions, it is possible that a road section has two functions. Then we speak of grey roads. Grey roads are not desired as the function and road layout can cause confusion to road users. In case grey roads are present at the chosen locations, possible solutions to improve grey roads mainly lie in applying a safe combination of layout characteristics and speeds that are tailored to the most vulnerable types of road users on that road section.

The Dutch road network can be distinguished in three main types. They can be further distinguished based on whether they are located in an urban or suburban area. The hierarchy of the American road network is roughly comparable, as can be seen in the table below. The values are derived from the earlier mentioned road design manuals.

Table 12 Comparison Dutch and American road hierarchy

The Netherlands	Speed limit Dutch roads (km/h)	United States	Speed limits American roads[1] (km/h)	Explanation for both countries
Stroomweg	100-130	Freeway	100-130	Flow function, serves to let high volumes of traffic flow
Gebiedsontsluitingsweg (suburban)	80	Arterial	50-80	Exchanges traffic from collector roads to freeways
Gebiedsontsluitingsweg (urban)/ Erftoegangsweg (suburban)	50/60	Collector and distributor	30-60	Exchanges traffic from local roads to arterials
Erftoegangsweg (urban)	30	Local	40	Exchange function, serves to give access to residences

Accordingly, questions are set up regarding this topic. The questions can be found in Appendix D.

5.2.2. (Bio)mechanics

The second principle, (bio)mechanics, is related to the homogenization of the traffic system. In other words, it is desired to limit the differences in speed, direction, mass and size, and giving road users appropriate protection.

This principle also takes account of the physical forgiveness of the traffic system. This is related to aspects such as whether there is enough space on the road in case maneuvers by road users is required, or to certain objects which may block the road or view.

Table 31 at the end of the desk investigation, derived from the Sustainable Safety report (SWOV, 2018a), was used which indicates the safe speed limits, each with its potential conflict situations and conditions associated therewith. Accordingly, questions are set up regarding this topic. The table and questions can be found in Appendix D.

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[1] Speed limits vary per state but are roughly as indicated in the table.

5.2.3. Psychology

Psychology is related to how well the traffic system is designed in a way that especially older road users are capable of recognizing how to safely participate in traffic. This means that even for them the information from the traffic system should be observable, self-explaining, credible, relevant, and executable. The coordination of traffic behavior with the task requirements to participate safely to traffic applies especially to traffic behavior at the strategic level and at the tactical level (SWOV, 2018a). These are based on Rasmussen's model of human behavior (Rasmussen, 1983). Strategic levels focus on aspects such as planning of trips, destination, route, and mode choice. Further, the maneuvering level is about negotiating in circumstances such as obstacle avoidance, gap acceptance and lane changing. A third level exists which is less relevant in this case, the control level. This level is about the actions performed inside a vehicle such as steering and braking.

Another distinction can be made for each task of road users. This distinction consists of knowledge-, rule-, and skill-based levels. Knowledge-based levels are about every action that is thought about in a conscious manner. On the other hand, rule-based levels are about consciously selecting a set of rules to a specific subtask, after which this subtask is performed automatically. The last level is skill-based, which is when the task is fully learned, and the driver no longer needs to think consciously about the task execution.

Examples of Rasmussen's model of human behavior is shown in the table below.

Table 13 Examples of the level of skills by Rasmussen (Wang, 2019). Operational/control is excluded for the psychology design principle.

	Strategic/planning	Tactical/maneuvering	Operational/control
Knowledge-based	Navigation in an unknown town	Negotiate intersection in case of snow	Skidding vehicle; novice driver (first lesson)
Rule-based	Choice between familiar routes	Overtaking maneuvers	Driving in an unfamiliar vehicle
Skill-based	Home-work travel	Negotiate familiar junctions	Vehicle handling in curves

In order to take account of the behavioral aspect of road users into the road design, the questions will mainly focus on the recognizability of elements for different road users within the traffic system. When a traffic system is designed in a way that a high recognizability is perceived, driving tasks such as negotiating familiar junctions or navigating in an unknown town (see, Table 13) will be performed more smoothly in favor of traffic safety.

Uniformity plays an important role regarding recognizability. Uniformity is realized when roads are designed according to the corresponding design guidelines. Based on the road design, road users should be able to recognize the right context for their actions. Small deviations from the guidelines are allowed, however, these differences should not be significant in a way that it could confuse road users.

First, it is determined what type of lanes are present per road for every alternative. The concerned roads are indicated with numbers on a map. Thereafter, it is determined whether the lanes are designed according to American guidelines. A table with three columns is made. The first column is for the width measured in Google Maps/Earth. The second column shows the sizes from the American guidelines. The last column indicates whether the lanes meet the guidelines. If guidelines are not met, screenshots with additional clarification are shown of the situations. A similar approach is done with respect to Dutch guidelines.

5.3. Results

For the results of the desk investigation, reference is made to Appendix D. The locations will again be illustrated below. Furthermore, it is also briefly explained what the results are per alternative and per Sustainable Safety principle.

Figure 11 Left-top: MUT (location 1). Right-top: QR (location 2). Left-bottom: DLT interchange (location 3). Right-bottom: SPUI. For larger images, see Appendix D.

5.3.1. Functionality

Location 1 is on Poplar Tent Road near Derita Road, Concord, N.C. A maximum speed of 45 mph (70 km/h) applies to both intersecting roads. For the purpose of functionality, both roads were designed as arterials. Road 2 provides access to industrial and business parks. This is done via separate auxiliary lanes. This makes it possible to drive 70 km/h on the through lanes. This can be done on the basis of both the Dutch and American guidelines.

In the Netherlands, both roads would be categorized as suburban arterials with a maximum speed of 80 km/h. In this case a physically separated sidewalk should be used, according to Dutch guidelines. Regarding the principle of functionality, this is the only modification that is necessary to make the traffic system meet the set of requirements for this Sustainable Safety principle.

At location 2 with the Quadrant Roadway, road section 2.1 is located within an urban area and provides access to residentials. The other road sections lie outside the urban area (i.e., suburban) and exchange traffic in a higher order. The signs present correspond to the actual function of the road sections.

At location 3 with the Diverging Diamond Interchange (DDI), the maximum speed is 70 mph (110 km/h) on the highway (road 2). Road 1 has a speed of 30 mph (50 km/h) at the intersections. After the intersections, the speed increases to 45 mph (70 km/h). Road 1 is designed as an arterial.

The two intersecting roads at location 4 with the SPUI consist of an arterial and a collector/distributor. Road 1 provides access to adjacent business parks. Here, a maximum speed of 35 mph (55 km/h) applies. There is a maximum speed of 45 mph (70 km/h) on road 2. This road exchanges traffic ahead with a higher order highway (interstate highway 495). For this reason, this is an arterial. For the exits, a maximum speed of 35 mph (55 km/h) applies, which corresponds to road 1.

5.3.2. (Bio)mechanics

All four locations make use of intersections, crossovers and/or U-Turns (i.e., places where road users intersect), that are all signalized. This means that regarding (bio)mechanics, potential conflicts can only occur with red light negation at all four locations. For location 2 it also applies that these can occur when the direction markers are crossed consciously or unconsciously. Furthermore, Table 31 (SWOV, 2018) and Table 34 and Table 35 (CROW, 2013) in the appendix indicate that the sight distances comply with the Dutch guidelines. Both CROW and SWOV have their own guidelines for stopping sight distances. Because no significant differences are noted, the SWOV guidelines were used.

5.3.3. Psychology

The widths of different types of lanes were tested on the basis of the American and Dutch design guidelines. The ERBI (Provincie Noord-Holland, 2021) was used for the dimensions. The ERBI describes the requirements and guidelines with which Dutch roads and road-bound facilities managed by the province of Noord-Holland must comply. The basis for the requirements and guidelines is, among other things, the CROW publications. The ERBI is in line with these guidelines as much as possible, but with a number of adjustments. In this case, the only difference is that, according to the CROW (2013), a minimum lane width of 2.75 meters applies on collector/distributor roads and arterials. A minimum width of 3.0 meters is maintained in the ERBI. Other widths correspond to the dimensions from the CROW.

Reference is made to Appendix D, where the comparison in Dutch and American design guidelines for lane widths is shown. Based on this, for location 1, both intersecting roads meet the American guidelines. However, a number of adjustments are necessary on the basis of the Dutch guidelines. The (auxiliary) lanes are too wide and may only be 3.0 to 3.10 meters wide. The narrow-paved shoulders should also be less wide. A width of 0.30 meters applies to arterials.

The Quadrant Roadway on location 2 is completely designed and constructed according to American guidelines. When the comparison is made with the Dutch guidelines, there are several lanes present that do not comply with this.

Here too, the narrow-paved shoulders should be less wide. A width of 0.30 meters applies arterials.

Furthermore, the width of the lane on road section 2.2 is 10 centimeters too short, however, this is negligible.

Road section 3, the connection road, which can be seen as a turn. The lanes on this road section are too wide. According to the CROW (2002), an extra widening of these curves of 0.50 meters per lane must be taken into account. Even with the extra width, the lanes do not meet the Dutch guidelines.

On the other hand, the emergency lane on road section 3 is too narrow and therefore does not comply with Dutch guidelines. Low intensity traffic is believed to be present on the connection road of the Quadrant Roadway. This is only intended for left-turning traffic. Through traffic generally has a higher traffic intensity. For this reason, the width of the emergency lane differs from that on the connection road with the surrounding roads. These emergency lanes are also constructed to support diverting freight traffic by giving them extra space to take the turn.

At location 3 with the DDI, road 2 is a highway. This was taken into account because the design of the highway falls outside the scope of this study. Only the fact that a highway is present as a bypass over the intersection platform was taken into account. For the lanes themselves, it also applies here that the narrow-paved shoulders of 0.60 meters are too wide. The (auxiliary) lanes are also too wide and have a width of 3.60 meters. These may only be 3.0 to 3.10 meters wide. All other lane types comply with the Dutch guidelines.

For location 4 with the SPUI both intersecting roads meet the American guidelines. Only the narrow-paved shoulder does not comply on road 2. It is probably extra wide due to the absence of a real median.

Several adjustments are necessary based on the Dutch guidelines. Road 2 gives the impression of a Dutch highway. This is partly due to the number of (wide) lanes. The (auxiliary) lanes are too wide and may only be 3.0 to 3.10 meters wide. The narrow-paved shoulders should also be less wide. A width of 0.30 meters applies to arterials in the Netherlands.

Finally, for all alternatives, heavy snowfall where road markings are obstructed can cause confusion. Especially for road users who are not familiar with the design. This may cause dangerous situations, especially when vulnerable road users, such as pedestrians and cyclists are present at the locations. In this case, only road signs are provided to assist drivers in navigating the intersection.

5.4. Conclusion

In this chapter, a desk investigation is constructed using the Sustainable Safety principles, along with the American and Dutch design guidelines. For this desk investigation, criteria of the Sustainable Safety principles are rephrased to questions which only the author of this study has given answer to for each of the designs, based on observations made through Google Maps/Street View. Therewith, an answer is provided regarding the second sub question. The question is defined as follows:

If these structures were to be built in the Netherlands, the way they are in the United States, what are the necessary modifications to meet the Dutch criteria for traffic safety and road design guidelines?

Based on the desk investigations, the traffic safety is evaluated, and the necessary modifications are determined. The speeds and road signs correspond to the types of roads present in the locations. This also applies to the intersections and interchanges themselves. Depending on the speeds, sufficient protection is offered to traffic whereby as the speed increases, the number of possible types of conflicts decreases.

Regarding the necessary modifications, only at the first location it was observed that there is no physical separation between motorized traffic and slow traffic. This would be necessary in the Netherlands on roads where the maximum speed is at least 50 km/h. Further, for the sake of uniformity of roads, it must be ensured that the correct dimensions are used for all types of lanes under Dutch conditions. Many (auxiliary) lanes are too wide and have a width of 3.60 meters. In the Netherlands, a width of 3.0 to 3.10 meters would apply for the comparable road type. Similarly for narrow-paved shoulders, which were usually 0.60 meters. A width of 0.30 meters applies to Dutch arterials.

All in all, based on all three design principles, all four designs meet the requirements set in the field of Sustainable Safety, provided that a number of plausible adjustments are made to the widths of the lanes. Each variant therefore has no critical peculiarity, which would make the application of the design in the Netherlands undesirable. For this reason, all four designs were included for further research in this study.

6

Traffic models study

To determine the impact of the unconventional designs on traffic flow, traffic safety, and the impact on their surroundings, traffic models were built. The commercial microscopic traffic simulation package PARAMICS was used for this study. In PARAMICS, complex road networks can be modeled involving different modes and thus various type of road users. As PARAMICS builds microscopic models, it can take into account the characteristics of each vehicle present in the designed road network. This way, the model represents the real traffic behavior more properly, especially in congested situations. Other simulation software exist that serve the same purpose as PARAMICS and also may give similar results. In Chapter 2, the reasoning behind choosing PARAMICS was described in detail, but in short, the main reason was due to the personal and positive experience with this software package.

The first section of this chapter gives a general description of the two chosen locations that were used for the traffic models. Hereafter, in Section 6.2, a part of the workshop held at the province Noord-Holland is described which gives an additional justification of the chosen unconventional designs (MUT, QR, DDI, and SPUI). Further, the technical characteristics of the chosen locations are presented, which formed the input for the traffic models. Then, several sections, starting at Section 6.6 presents the results from traffic models. This includes the impact of each design on traffic flow, traffic safety, and the impact on their surroundings. Section 6.9 explains another part of the workshop where the implementation of new infrastructural designs was discussed. Finally, this chapter ends with conclusions, answering the third and fourth sub question.

6.1. General description - Current (reference) situations

This section gives a general description of the two locations that were chosen to be used as reference situations in the traffic models.

Before the locations were chosen, it was aimed to pick two locations from which one included an intersection, and the other one an interchange. Since this thesis is performed with the guidance of the province, the decision was made to only pick locations within the province Noord-Holland due to the (direct) availability of traffic-related data. The province owns most of the N-roads within the province. Further, it was aimed to choose locations that resemble typical Dutch circumstances. Not only does this include Dutch traffic volumes, but, if possible, also includes pedestrians, cyclists, and public transport.

Location 1: N196 – N231

For the first location, the aim was to pick a four-legged intersection as both the Median U-Turn (MUT) and the Quadrant Roadway (QR) can be used as an alternative for this type of intersection. Location 1 consists of a traditional four-legged intersection nearby Aalsmeer and Hoofddorp. Currently, the intersection is being reconstructed. As traffic data is not available of this new situation yet, the old situation was used for this study. The location is shown in Figure 12, and zoomed into the intersection part in Figure 13.

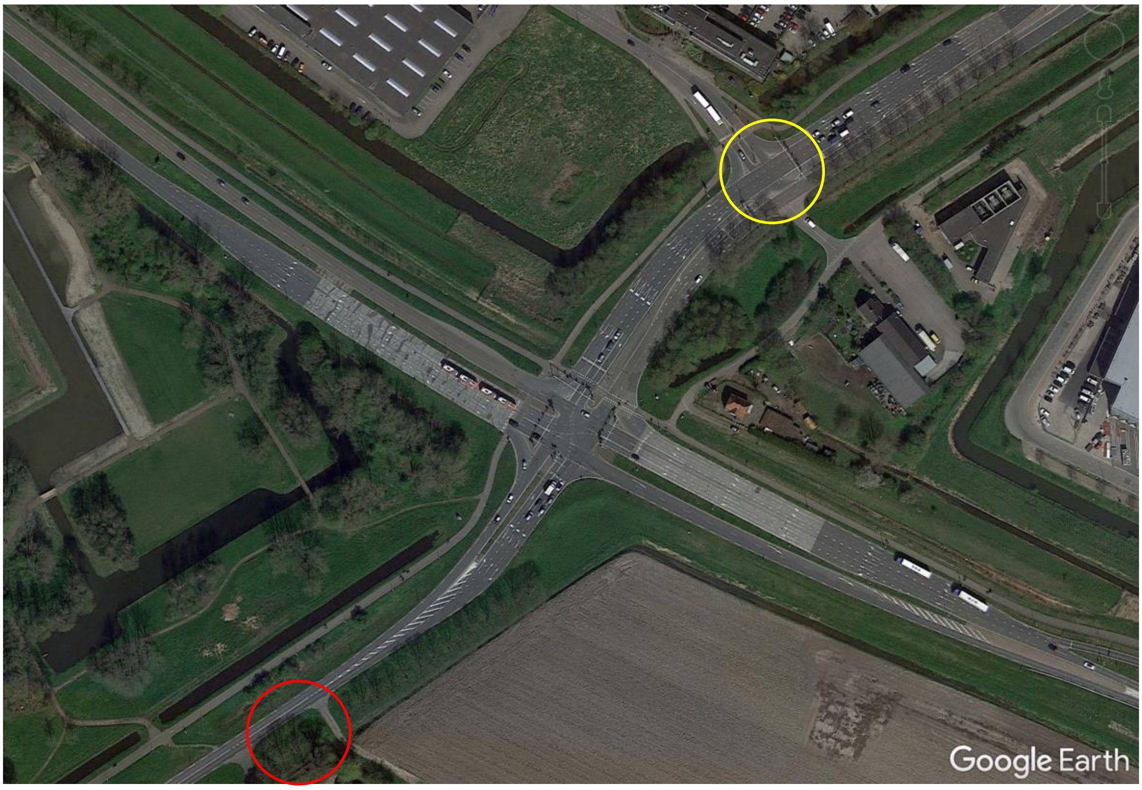


Figure 12 Location 1 nearby Aalsmeer. Road from East to West is the N196. From North to South is the N231.

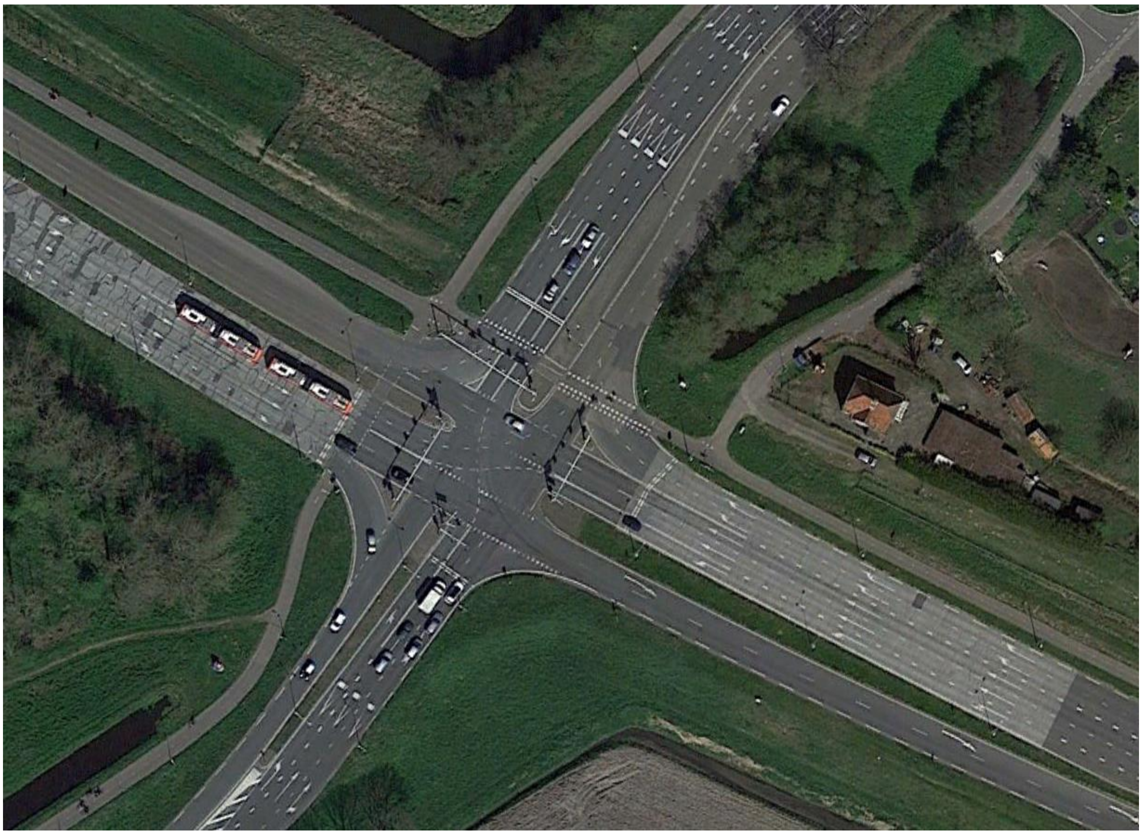


Figure 13 Location 1 four-legged traditional intersection.

Here, traffic is being exchanged at grade, with the presence of slow traffic (pedestrians and cyclists) and public transport. The slow traffic is protected by signals and can cross the road on the North and on the West side of the intersection. Further, there is one bus line going from East to West and vice versa. During the morning peak hour, the frequencies are eight buses per hour to the West and five buses per hour to the East. No bus stops are present nearby the intersection.

On this South side, nearby zone 001, a house is located (see, Figure 12 circled in red). Regarding the QR, it is difficult to use this design with the presence of this house. Therefore, for this study it was assumed that the house did not exist, and that permission was granted to build the connector road of the QR on the green plain in the Southeast area. Lastly, the intersection located on the Nord side was disregarded as well (see, Figure 12 circled in yellow). This intersection exchanges traffic from residential areas nearby but was not expected to significantly affect the traffic flow of the main intersection this study focuses on. Thus, to avoid making the model unnecessarily complex, it was disregarded.

Location 2: N244 – A7

For the second location, the aim was to choose a four-legged interchange within the province. A grade-separated interchange consists of at least one N-road. Not too many options were available as most interchanges only consisted of three legs. The second location chosen is the N244-A7, nearby Purmerend. The main advantage of this location is that there is a sufficient amount of space to make reconstructions possible, and the current connections are not too complex. This in turn makes it more convenient to replace the current design by the Diverging Diamond Interchange (DDI) interchange and the Single-Point Urban Interchange (SPUI).

The current situation has a Partial Cloverleaf (Parclo) Interchange. It consists of two signalized intersections, along with a highway that goes underneath. The entrances and exits that are connected to the intersections are all in line with the direction of travel on the highway. No slow traffic (pedestrians and cyclists), nor public transport is present on this location. The location is shown in Figure 14, and zoomed into the interchange in Figure 15.

Figure 14 Location 2 nearby Purmerend. Road from East to West is the N244. The highway from North to South is the A7.

Figure 15 Location 2 Parclo interchange.

A critical assumption was made for the second location. The road section on the North of the Eastern intersection that leads to an urban area (see, Figure 14 circled in red), causes the unconventional designs to be modified in a way that they do not function anymore as intended. To avoid this issue, the assumption was made that traffic going/coming from the northern road section gets rerouted elsewhere. This northern road can then be disregarded, and the interchange shall then consist of two three-legged intersections. To keep the comparisons between designs fair, this northern road section was disregarded from all, including the current situation.

6.2. Expert judgment on the traffic modeling case studies

On June 24th, a workshop was held at the province Noord-Holland in the form of a workshop. Twenty-two people got invited from which eleven were present. The audience consisted of members of different departments and sectors, among which road design, policy, traffic safety, management, and mobility. The goal of the workshop was, among others, to gain insight in how experts and professionals of the province think of unconventional designs, as they have a different working method at the province. Further, to discuss two cases where designs chosen in the previous chapter (MUT, QR, DDI, and SPUI) could be built. For this chapter, the important slides are the ones focusing on these case studies with the four designs. The two chosen locations are described in the previous section. The highlights of the workshop, including all the slides of the presentation, can be found in Appendix F. It must be noted that the workshop was held in Dutch.

During the part of the workshop where the case studies with the four designs are presented, it was asked to the experts and professionals whether they thought each one of the designs were interesting for further research. In other words, a research through traffic modelling. For the first location it was chosen to build the QR and MUT. The opinions were divided for the QR, as the QR shows theoretically to have benefits regarding improving the traffic flow. On the other hand, it was argued that despite the fact that left-turns are rerouted, the addition of two more intersections might still cause a negative impact on traffic safety. Building traffic models in this case is helpful to determine the impact of the QR on traffic safety. Further, many of the experts and professionals had a positive opinion regarding the MUT. It was mentioned that the efficient use of space is a great benefit, especially in the Netherlands with the increasing urbanization. This in turn reflects that it is beneficial to build traffic models for the MUT.

For the second locations it was chosen to build the DDI and SPUI. Despite the differences in the given answers, the argumentation for both the designs were similar. Both the designs themselves were fine. The compactness of the design and the improved traffic flow were the main reasons for this. However, it was argued that chosen location might not be suitable. This second location does not have many left-turning traffic, while both the DDI and SPUI are usually considered at locations with heavy left-turning traffic volumes. For this reason, it was suggested to either increase the traffic volumes of left-turns, or pick another location. At the time the workshop was held, the traffic models were already built at an advanced stage. Due to conveniency, it was chosen to increase the number of left-turns instead of picking a new location. How much the left-turning traffic volumes were increased, will be discussed in the next subsection.

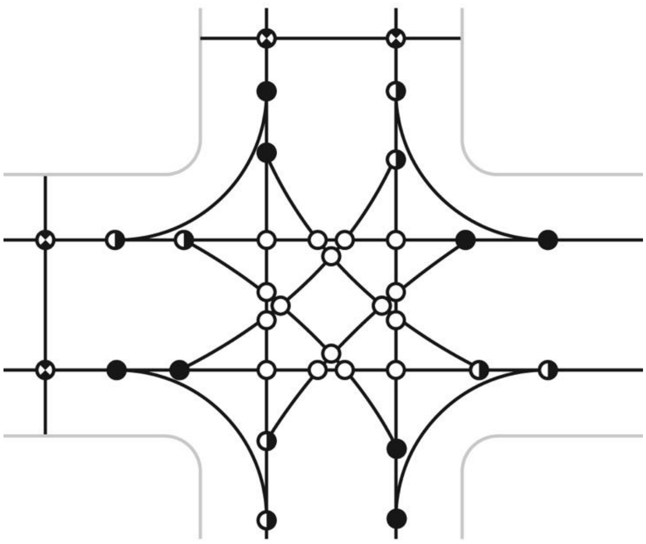
Earlier in this report (Chapter 4), the MUT, QR, DDI, and the SPUI were chosen through a multi-criteria analysis, based on their reported advantages and disadvantages from scientific literature. Hereafter, in Chapter 5, the extent of the four designs were analyzed to which they comply to the Dutch rules and guidelines. Only small, plausible adjustments were necessary, but none of the four designs needed to be disregarded for further research. Moreover, during the workshop at the province, the opinions regarding all four chosen designs were generally positive. All in all, this means building traffic models for the MUT, QR, DDI, and the SPUI are additionally justified.

6.3. Technical characteristics - Current (reference) situations

In subsection 6.1, a general description was given of the reference situations. Accordingly, this subsection discusses the technical characteristics of these chosen locations more in detail. This includes the conflict types, traffic signals, zones, OD-matrices, simulation time, and conflict analysis.

Conflict types

One of the ways to evaluate the traffic safety is by comparing the number of conflict points of the current locations with the unconventional designs. Conflict points are locations on the intersection/interchange where the paths of road users intersect. In this study, the vehicle-vehicle conflict types were classified in three categories: crossing, merging, or diverging conflict points. Additionally, the vehicle-cyclist/pedestrian conflict points are taken into account as well. Figure 16 and Figure 17 show the movements of the road users, along with the associated conflict points of the design of the current situation. Similarly, this is shown for location 2 in Figure 18 and Figure 19.



Symbol	Conflict type	Number of conflicts
	Crossing	16
	Merging	8
	Diverging	8
	Vehicle-Cyclist/Pedestrian	4

Figure 16 Number of conflicts on location 1, current situation

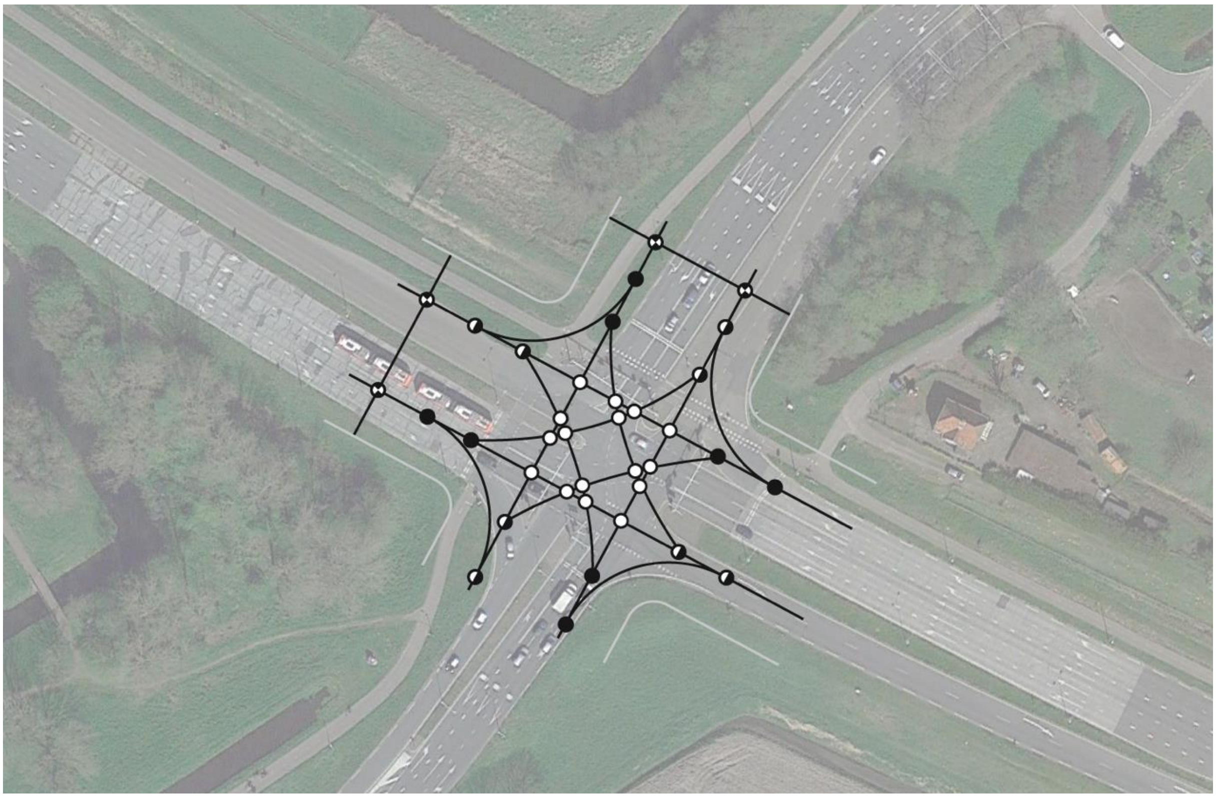
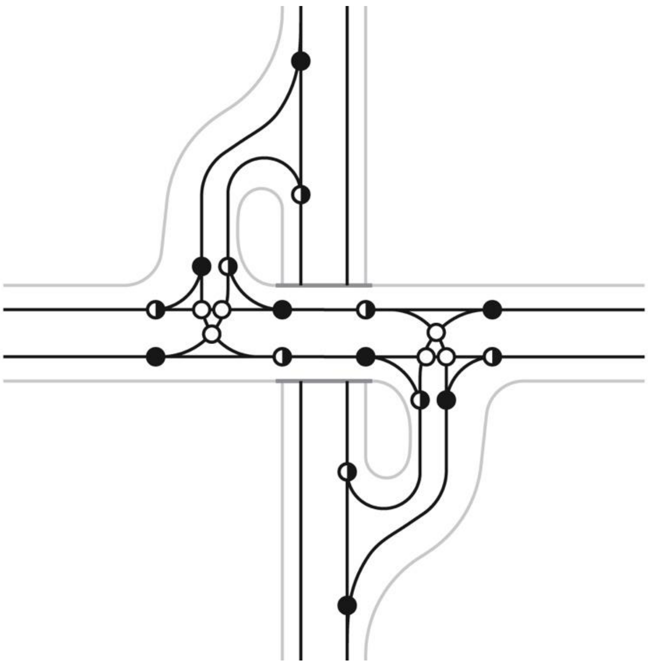


Figure 17 Conflict points plotted on location 1 (not on scale)



Symbol	Conflict type	Number of conflicts
○	Crossing	6
◐	Merging	8
●	Diverging	8

Figure 18 Number of conflicts on location 2, current situation

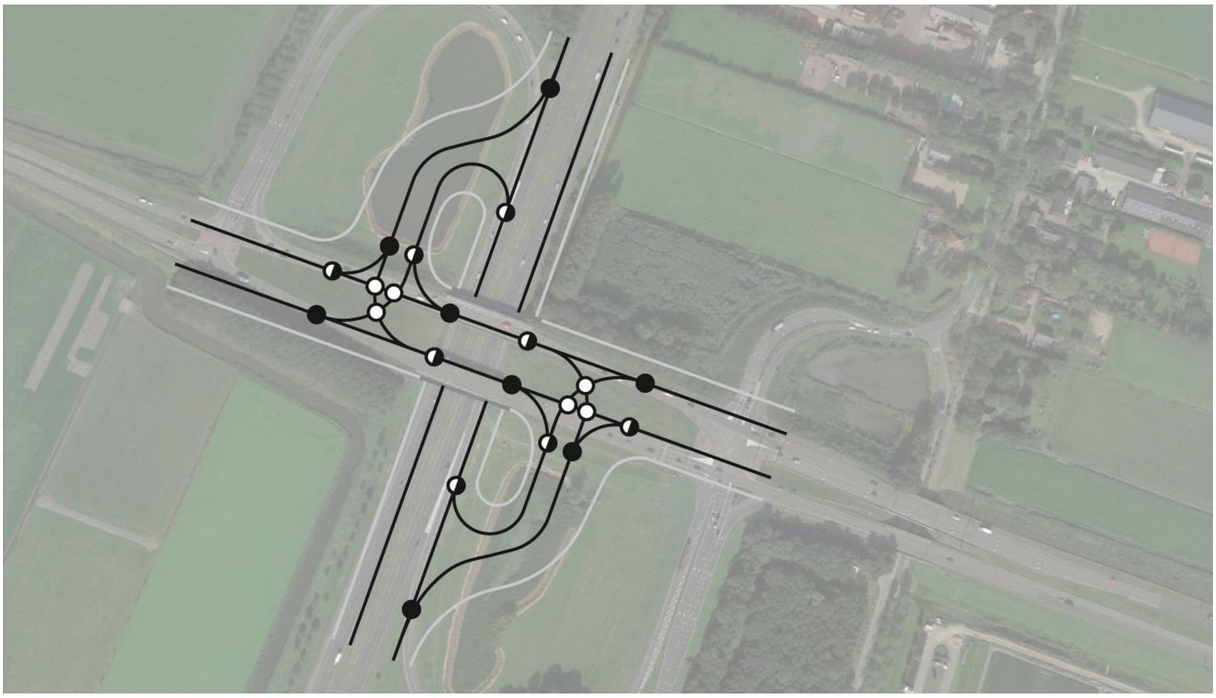


Figure 19 Conflict points plotted on location 2 (not on scale)

Traffic signals

With certain models, green waves are necessary when multiple intersections are present in the road network. Due to the complexity of applying green waves into the model, a more pragmatic approach was chosen by turning the fixed signals into vehicle-actuated signals. With the use of detectors, the model can decide whether to give a fixed extra green time during a phase. If it is necessary, then the maximum green time is used. Otherwise, the traffic shall flow according to the minimal green time during that phase.

The distance between a detector and an intersection matters. When the distance is large, it means that the lane allows to have a relatively large queue. When the detector is placed closer to the intersection, it means that the detector will be activated with shorter queues. As a result, the maximum green time is given more often.

The signal phasing scheme, including the signal controller settings were data provided by the province. This data is used as part of the input and processed in the traffic model. shown of both locations below. Table 14 and Figure 20 are provided data that apply to the first (reference) location with the traditional four-legged intersection. Similarly for the second (reference) location with the Parclo interchange, Table 15 and Figure 21 are data provided for the western intersection, while Table 16 and Figure 22 are data provided for the eastern intersection of the Parclo. These tables and figures explain the traffic signal operations. The signal phasing schemes show how the cycle times are divided. Subsequently, the corresponding figures show per phase (in green) to which directions the green times are allocated.

Table 14 Signal phasing scheme location 1

Location 1	Phases			
	1	2	3	4
Min green	39.0	11.0	6.0	17.0
Max green	39.0	11.0	6.0	17.0
Amber	3.0	3.0	3.0	3.0
All red	0.0	0.0	0.0	0.0
Ped walk[2]	7.0	0.0	0.0	7.0
Ped clearance[2]	14.0	0.0	0.0	14.0

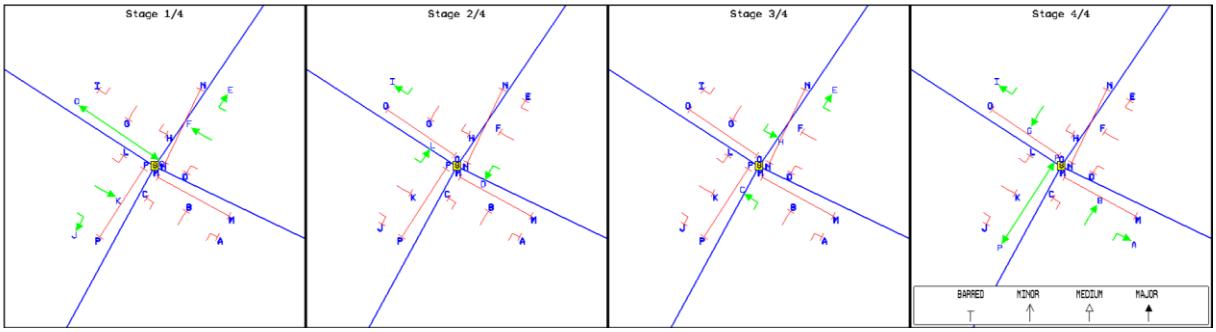


Figure 20 Signal controller settings location 1

Table 15 Signal phasing scheme location 2, western intersection

Location 2 West	Phases		
	1	2	3
Min green	36.0	18.0	15.0
Max green	36.0	18.0	15.0
Amber	3.0	3.0	3.0
All red	0.0	0.0	0.0
Ped walk	0.0	0.0	0.0
Ped clearance	0.0	0.0	0.0

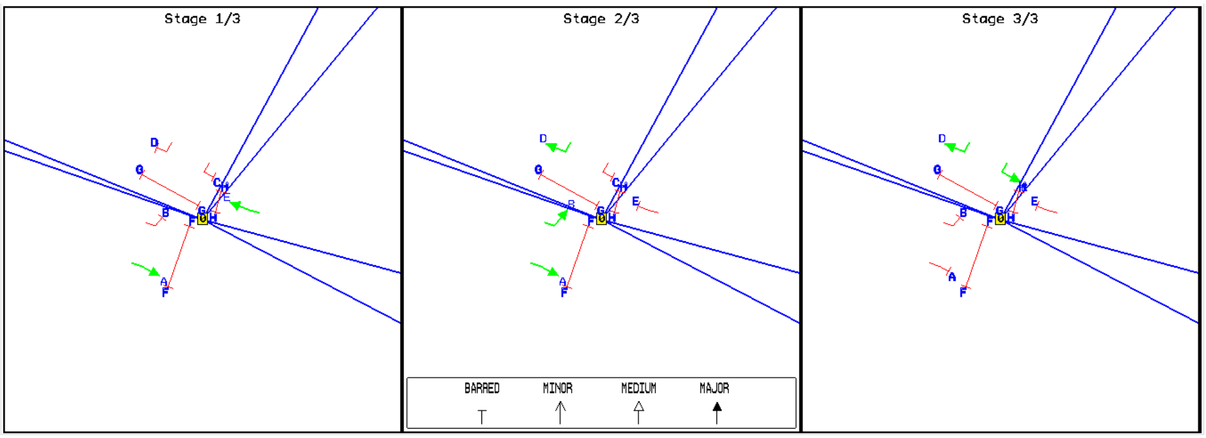


Figure 21 Signal controller settings location 2, western intersection

[2] The times for pedestrians to walk and their clearance time is unknown. Hence, the same values are used that are known for the American intersections. These are 7.0 and 14.0 seconds, respectively. These times fall within the green times given to the corresponding phase.

Table 16 Signal phasing scheme location 2, eastern intersection

Location 2 East	Phases	
	1	2
Min green	20.0	15.0
Max green	20.0	15.0
Amber	3.0	3.0
All red	0.0	0.0
Ped walk	0.0	0.0
Ped clearance	0.0	0.0

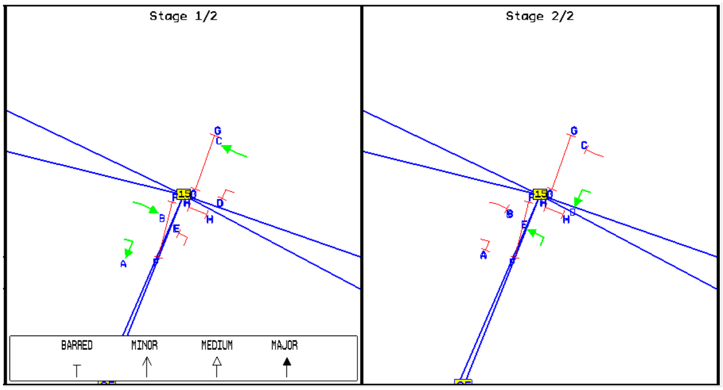


Figure 22 Signal controller settings location 2, eastern intersection

Zones

The zones indicate where traffic comes from or goes to. Both locations require four zones, which are allocated similarly. This is shown in the table below.

Table 17 Zone allocation for both locations

Direction	Zone number
South	Zone 001
West	Zone 002
North	Zone 003
East	Zone 004

Origin-Destination matrices

By creating OD-matrices the traffic volumes were shown that go from zone to zone. The traffic volumes are expressed as the number of vehicles per hour. Highlighted are the traffic volumes that were known on beforehand through the data provided by the province. The remaining traffic volumes were estimated based on the number of lanes a direction has, the green time given to these directions from known data, and the attractiveness of the zones where the traffic goes to or comes from. For instance, certain zones might lead to cities, which are more attractive to commuters during the morning peak hours. In that case a higher traffic volume is to be expected.

The OD-matrix of location 1 is shown below. The traffic volumes are depicted from October 15th, 2020, on a Thursday during the morning peak hour (08:00-09:00). Due to the amount of work these models require, it was chosen only to model the morning peak hours in this study. In the evening, traffic volumes may differ in certain directions, leading to different results. Therefore, it is recommended to model the evening peak hours as well in further research (see, Section 8.2).

Table 18 OD-matrix location 1. Highlighted are known values.

	001	002	003	004	Total origin
001	xxx	147	296	178	621
002	131	xxx	178	348	657
003	126	332	xxx	83	541
004	87	890	267	xxx	1244
Total destination	344	1369	741	609	3063

The OD-matrix of location 1 shows that most traffic comes from the East and goes to the West. This is logical as in the West, Aalsmeer and Hoofddorp are located, and therefore, highly attractive to commuters. The road section on the North is part of a long route, which eventually ends up nearby Schiphol. Nonetheless, this zone (003) remains not as popular as the zone to Aalsmeer/Hoofddorp (002). In the East (zone 004) there is Uithoorn nearby. This is the direction where most of the vehicles come from. The South (zone 001) is the least popular zone. No large cities are located nearby this zone.

The OD-matrix of location 2 is as follows. The traffic volumes are depicted from the average business days from January 1st to December 31st, in 2020, during the morning peak hour (08:00-08:59). The DDI, as well as the SPUI, are both designs that are considered at locations where heavy left-turning vehicles are located. This is not the case for this location. For this reason, it was chosen to increase all the left-turning OD-routes by 50% for these traffic models. By increasing the traffic volumes for those routes by 50%, the same number of lanes can be maintained, without the presence of very large congestions in the traffic model of the second (reference) situation.

Table 19 OD-matrix location 2. Highlighted are known values.

	001	002	003	004	Total origin
001	xxx	213	200	305	718
002	208	xxx	284	318	810
003	200	142	xxx	457	799
004	934	220	623	xxx	1466
Total destination	1342	575	1107	1080	4104

Also for this situation, most traffic comes from the East (zone 004). Most of this traffic then goes either straight ahead to the North (zone 003) or to the South (zone 001). All other zones have relatively low traffic volumes. Zone 001 and 004 lie directly nearby Purmerend. Zone 001 leads to the Randstad (i.e., Zaandam and Amsterdam), so relatively higher traffic volumes are to be expected going to this zone during the morning peak hours. Zone 003 leads to the northern area of the province (i.e., Hoorn). In the West there is a road leading to Alkmaar, which is a relatively large city. But surprisingly, according to the data, this traffic volume is quite low.

Simulation time

It was chosen to simulate every model for 2 hours. The first hour is meant to make the traffic get used to the road network. This means that this hour gives unreliable results and is discarded from the study. The second hour is used for further research. Also, the simulation does not end with an empty network, meaning that no demand profiles are assigned that can vary the demand of traffic within a simulated hour. Further, it must be noted that the seed values were not touched, and thus kept random. This means that in each simulation, vehicles enter the network at random times. Moreover, for each design only one simulation was run.

6.4. Traffic flow analysis

Performance indicators according to the simulation results were determined. These indicators are explained below:

1. Travel times (all trips)
   a. The average travel times of all vehicles from the same Origin-Destination (OD) route are determined. It is determined for all vehicles that are present within intervals of 10 minutes. The illustrated results (see, Section 6.6), however, do not show the OD-route, nor the time interval. Instead, all these average travel times are shown in one box plot. This creates a general impression in travel times in the whole simulated network, compared to other designs.
2. Travel time differences
   a. The results from the ‘Average travel time’ is used, where the results from an unconventional design is subtracted from the corresponding current (reference) situation. Accordingly, the impact on travel time of the unconventional designs becomes clear.
3. Vehicle counts
   a. Also here, intervals of 10 minutes apply. For example, when a data point indicates that vehicles on the same (OD) route have travelled by average 800 meters, it means the vehicles on that route that are present at the location in the 10 minutes interval.
4. Average distance travelled
   a. Designs such as the Median U-Turn reroute left-turns. This indicator shows how much extra distance in total is being travelled due to the rerouting. Long detours are not desired and could cause traffic congestion, leading to a negative impact on traffic flow.

These performance indicators are explained more in detail in Section 3.2.

6.5. Conflict analysis

PARAMICS creates outputs including the vehicle positions, their speeds, and other characteristics. With this data, a conflict analysis was performed. The following surrogate safety measures are determined:

1. Time-To-Collision (TTC)
   a. With this measure it becomes clear how many potential critical conflicts a design has. Comparing it to the current (reference) situation indicates the impact on traffic safety.
2. Post-Encroachment-Time (PET)

    a. This measure indicates 'near misses' between consecutive vehicles. As traffic gets rerouted, or drives differently than on traditional designs, post-encroachment-time may get affected as well. When this is compared to the current (reference) situation, a statement can be made regarding the impact on traffic safety.
3. Deceleration rate (MaxD)
    a. Harder decelerations indicate unsafe situations. The extent and severity to which these unsafe situations occur can be determined with this measure.
4. Speed differential (DeltaS)
    a. The difference in speed between consecutive vehicles should be low. The lower the speed differences, the larger the homogeneity in terms of speed. This implies a safer traffic situation (SWOV, 2018a).
5. Conflict types
    a. A reduced number of conflicts per conflict type, compared to the current (reference) situation indicates that less potential conflicts occur. This in turn shows an improvement in traffic safety.

These surrogate measures are explained more in detail in Section 3.2. Further, reference is made to the section regarding data analysis, where the procedure is explained to obtain the results out of the data exported from PARAMICS.

The measures can easily be determined with the SSAM software tool. However, since the output of PARAMICS was incompatible with SSAM, manual calculations were made to determine the results instead. Even though, SSAM could not be used, the default threshold values were adopted, as these values, according to Gettman (2008), were determined through a literature review.

Threshold values can be applied to the first four safety measures to make a distinction between severe and non-severe events. Research by De Ceunynck (2017) shows through his analysis what the most applied threshold value is, based on nineteen scientific publications. Most of these studies show that a threshold value of 1.5 seconds is applied to the TTC measure. Simultaneously, 1.5 is also the default threshold value used in SSAM. Hence, 1.5 was used as the threshold value for TTC in this study.

The same research by De Ceunynck (2017) shows that most scientific publications do not use a threshold value to take account of all traffic interaction. Also in this study all traffic interactions were taken into account, but values between 0.0 and 5.0 were divided to get a better indication to the near misses and actual accidents. Here, a value of 0.0 indicates an actual accident. Any PET value higher than 5.0 has an insignificant chance for collisions, thus no further distinction was made after 5.0.

Finally, MaxD and DeltaS were also determined. No literature was found that propose values different from the default settings used in SSAM. With the default settings, no threshold values are used. Similarly, no threshold values were used for these two safety measures in this study.

6.6. Case studies

Below, the traffic flow and traffic safety indicators/measures are determined and compared to their corresponding reference situation. The output for traffic flow is exported with intervals of 10 minutes within the peak hour. Regarding the output for traffic safety, all involved vehicles are taken into account within the peak hour.

6.6.1. Location 1 - Setup

Two unconventional designs are modelled at the first location. These are, the Median U-Turn (MUT) and the Quadrant Roadway (QR). This subsection describes first both designs, consisting of the adjustments that are made, and their signals configuration. Hereafter, the traffic model results are discussed, for each performance indicator and surrogate safety measure. Lastly, the impact of each design on their surroundings is briefly explained.

Median U-Turn (MUT)

The MUT was built on the first location with the existing traditional intersection. Compared to the current location, the following modifications were made:

- As left-turns are being rerouted, all the lanes for left turns were removed;
- An extra lane was added for vehicles wanting to make a U-Turn;
- The U-Turns themselves were added on the busiest road (N196);
- Traffic signals were adjusted at the main intersection, and added to the U-Turns.

Accordingly, the model looked as follows:

Figure 23 Median U-Turn alternative in PARAMICS

Signals configuration

The signals of the main intersection consists of three phases, while the U-Turns are designed with two phases. It is required to have a green wave between the main intersection and a U-Turn. But as explained before, for the model the signals are designed vehicle-actuated signals. Report by Hughes et al. (2010) suggests several variations for the design of the signals. From this, the most suitable signal configuration was chosen. This is depicted below.

Table 20 Signal phasing scheme main intersection MUT

MUT	Phases		
	1	2	3
Min green	15.0	4.0	4.0
Max green	30.0	20.0	20.0
Amber	3.0	3.0	3.0
All red	2.0	3.0	3.0
Ped walk	7.0	0.0	0.0
Ped clearance	14.0	0.0	0.0

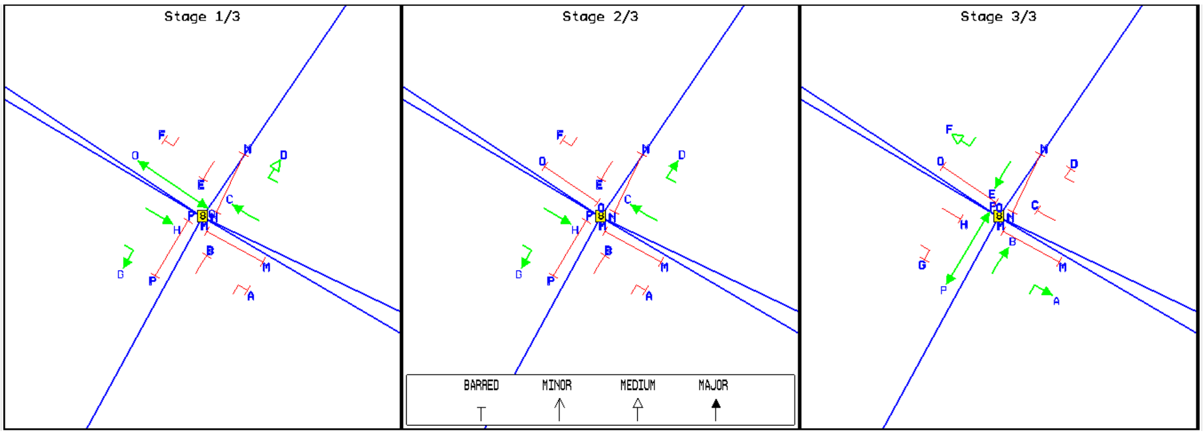


Figure 24 Signal controller settings main intersection MUT with overlaps

Table 21 Signal phasing scheme U-Turns of the MUT

U-Turns	Phases	
	1	2
Min green	15.0	4.0
Max green	30.0	20.0
Amber	3.0	3.0
All red	0.0	0.0
Ped walk	0.0	0.0
Ped clearance	0.0	0.0

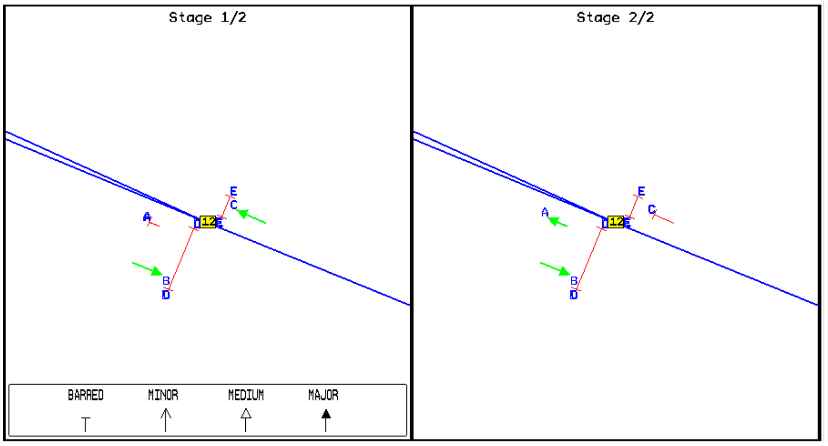


Figure 25 Signal controller settings U-Turns of the MUT

Quadrant Roadway (QR)

The QR was built on the first location with the existing traditional intersection. Compared to the current location, the following modifications were made:

- As left-turns are being rerouted, all the lanes for left turns were removed at the main intersection;
- The connector road should be built based on which left-turns carry the most traffic. However, space also plays a role in this situation. As can be observed in Figure 26, only space was available in the South-East quadrant. To keep the number of modifications low, the South-East quadrant was chosen;
- The secondary intersections were added with 2x1 lanes;
- Traffic signals were adjusted at the main intersection, and added to the secondary intersections.

Accordingly, the model looks as follows:

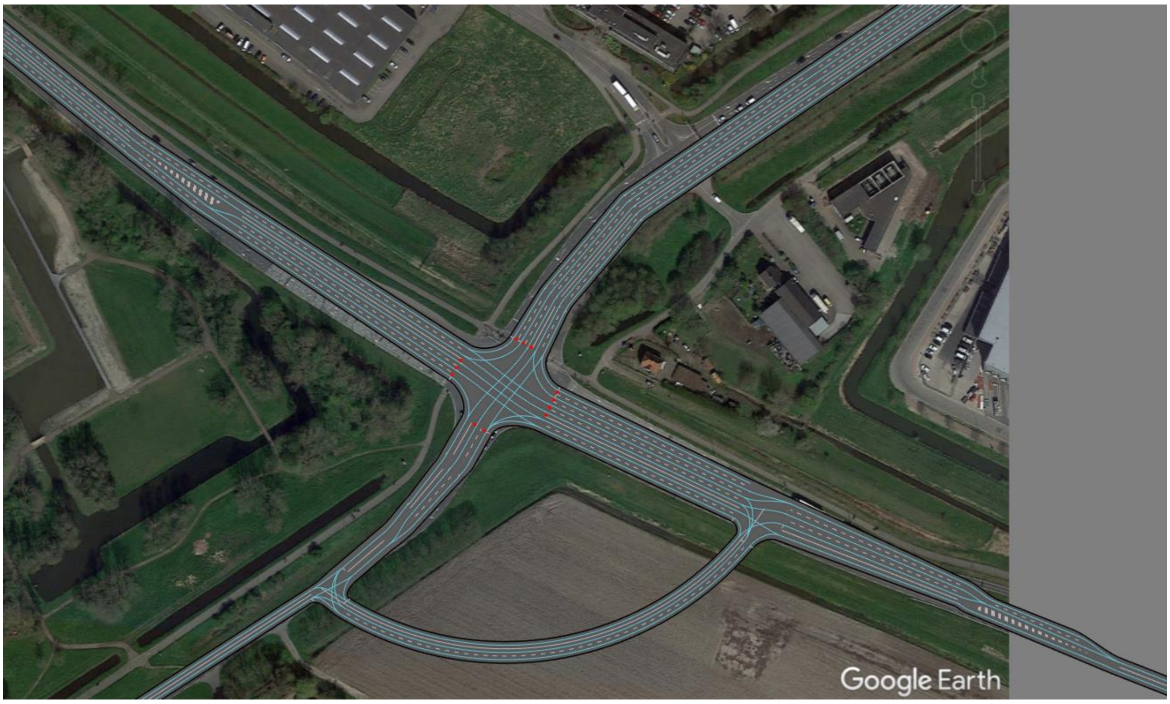


Figure 26 Quadrant Roadway alternative in PARAMICS

Signals configuration

The signals of the main intersection consists of two phases, while the secondary intersections are designed with three phases. It is required to have a green wave between the intersections. But as explained before, for the model the signals are designed as vehicle-actuated signals. Report by Hughes et al. (2010) suggests several variations for the design of the signals. From this, the most suitable signal configuration was chosen. This is depicted below.

QR main	Phases	
	1	2
Min green	15.0	4.0
Max green	30.0	20.0
Amber	3.0	3.0
All red	0.0	3.0
Ped walk	7.0	7.0
Ped clearance	14.0	14.0

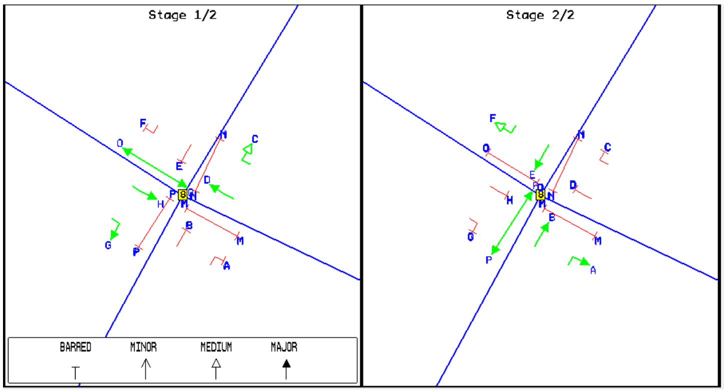


Figure 27 Phasing plan main intersection QR

QR secondary	Phases		
	1	2	3
Min green	15.0	15.0	15.0
Max green	30.0	30.0	20.0
Amber	3.0	3.0	3.0
All red	0.0	0.0	0.0
Ped walk	0.0	0.0	0.0
Ped clearance	0.0	0.0	0.0

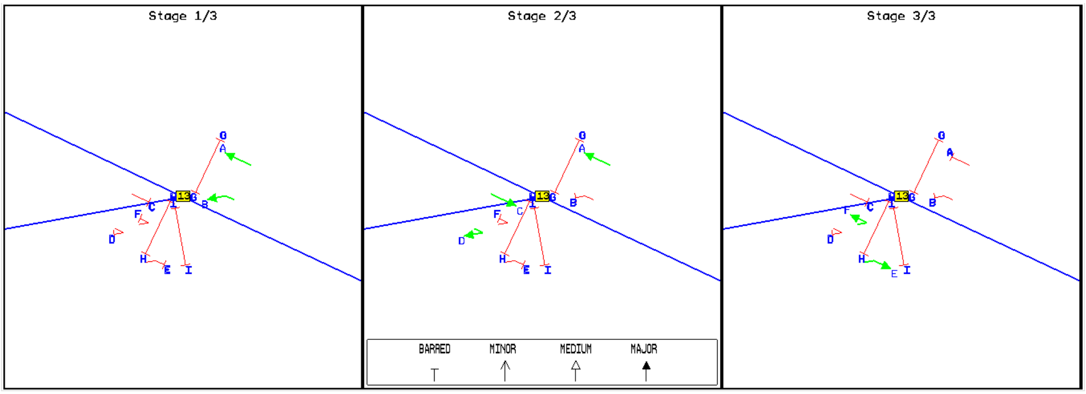


Figure 28 Phasing plan secondary intersections QR

6.6.2. Location 1 - Traffic modelling results

Impact on traffic flow

Below, the results of each traffic flow indicator is depicted for the MUT and QR. This includes the interpretation of the results, compared to the current situation.

As explained in Section 6.4, the following performance indicators for traffic flow are determined:

1. Travel times (all trips)
2. Travel time differences
3. Vehicle counts
4. Average distance travelled

Travel times (all trips)

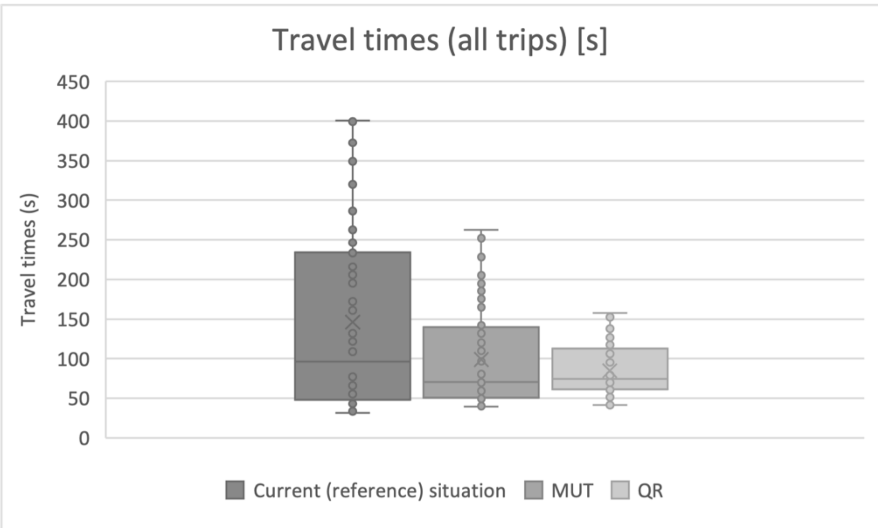


Figure 29 Travel times (all trips) of the MUT and QR, compared with the current situation

The average travel times of the whole traffic situation are depicted in Figure 29. A significant difference can be noticed between the unconventional designs and the current (reference) situation.

The MUT reroutes left-turns with the use of U-Turns. These results show that the lanes that are additionally being used by rerouted left-turning vehicles, were well capable of handling these traffic volumes. Also, the reduction in the number of phases of the traffic signals at the main intersection contributed to the improved traffic flow. The number of phases was reduced as a consequence of rerouting left-turns.

What can be noticed regarding the QR is that the shortest travel times were experienced. On the other hand, the median of the box plot does appear to be quite similar to the MUT. Nonetheless, by adding two more intersections and a connector road to the reference situation, the rerouting of left-turns does not negatively impact the overall travel time at the location. The intersections are located quite close to each other, but due to the vehicle-actuated signals, traffic progresses more sufficiently through network.

All in all, the results show for both the MUT and QR a significant improvement in travel times, compared to the current (reference) situation. When determining the percentual differences, based on the median of the box plots, an average improvement of the MUT and QR was observed to be 27% and 22%, respectively.

Travel time differences

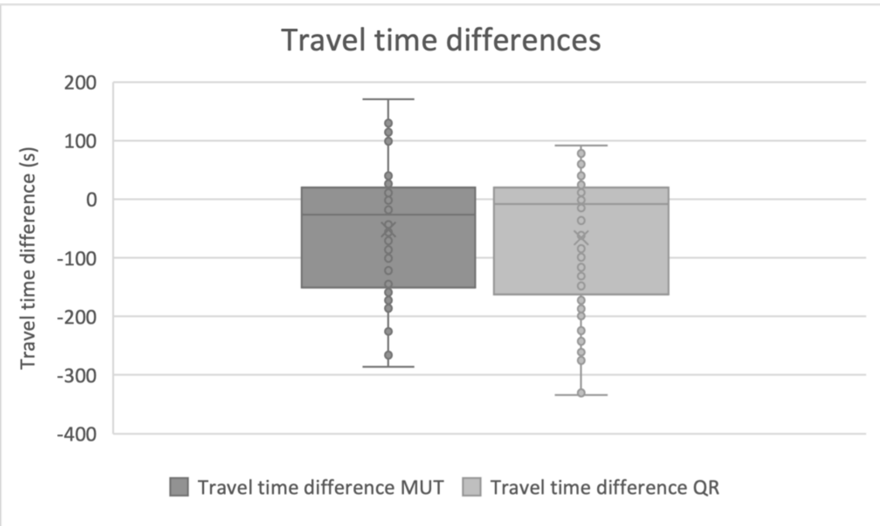


Figure 30 Travel time differences of the MUT and QR, compared with the current situation

When the travel times from the new situation with the MUT or QR is subtracted from current situation, the travel time differences can be illustrated. These are shown in Figure 30. Most data points appear to be negative, the boxes themselves are also mostly on the negative side. This observation shows that the travel times, compared to the current (reference) situation, improves, but there are several occasions observed that the current (reference) situation performs more efficient than the unconventional designs. When comparing the medians of the box plots, an improvement of nearly 27 seconds is observed for the MUT, while for the QR, the travel times improve with approximately 8 seconds.

Vehicle counts

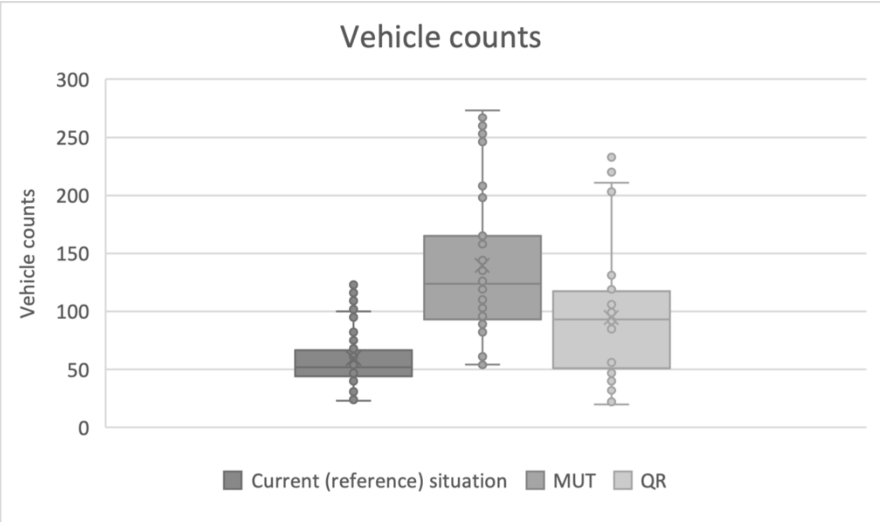


Figure 31 Average vehicle counts on the MUT and QR, compared with the current situation

The vehicle counts show how much traffic is present in a certain period. Figure 31 shows that during the simulated peak hour, the MUT allows more vehicles in the area than the current situation. On most occasions, this is also the case for the QR. When comparing the medians of each box plot, an increase of 138% for the MUT and 79% for the QR are observed. This can mean two things; if the travel times increase, compared to the current situation, it means, together with the increase in vehicle counts, that the network has a small capacity. On the other hand, if the travel times decrease, compared to the current situation, it means, together with the increase in vehicle counts, that the network has a large capacity. In other words, to make a statement on the results for vehicle counts, the results of the travel times and travel time differences also influence this statement.

It was shown earlier that the travel time improves. Thus, the vehicle counts indicate that the MUT and QR have a larger capacity than the current situation.

Average distance travelled

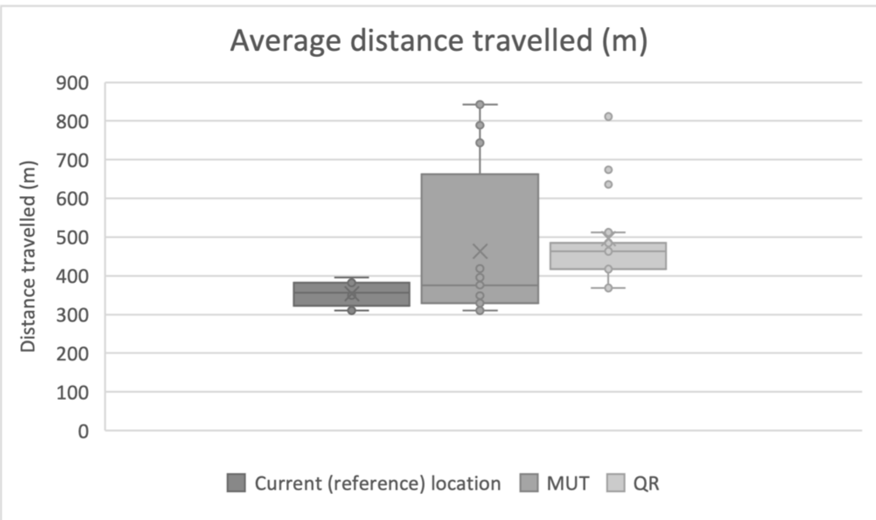


Figure 32 Average distance travelled on the MUT and QR, compared with the current situation

When the average distance travelled between the unconventional designs and the current situation is compared, it can be noticed that during the whole simulated peak hour, vehicles have to travel significantly longer distances with the MUT. The box of the MUT is large, meaning that the travelled distances experienced differ a lot. But the median appeared to be quite similar to the current situation. When comparing the medians of the MUT with the reference situation, an increase of 5% was observed. This observation corresponds to the way the MUT works, as left-turns are rerouted. As a result, longer distances are travelled by these vehicles specifically.

Further, the QR shows quite significant results, with some outliers. The QR also reroutes all left-turns on the main intersection with the use of the connector road. As can be seen in Figure 6, the QR works in a way that left-turns from certain approaches either have a longer route or a shorter route. Despite the longer route for certain traffic, the distances travelled on a QR appeared not to have too many significant differences, leading to a smaller box. Its median is positioned higher than the other box plots, meaning that most vehicles travel approximately 450 meters. Expressed in percentual differences, this means an increase of 30%, compared to the current situation.

Impact on traffic safety

Below, the results of each surrogate safety measure is depicted. This includes the interpretation of the results, compared to the current situation.

As explained in Section 6.5, the following surrogate safety measures are determined:

1. Conflict types
2. Time-To-Collision (TTC)
3. Post-Encroachment-Time (PET)
4. Deceleration rate (MaxD)
5. Speed differentials (DeltaS)

Conflict types

Regarding the possible conflicts, vehicular movements (and the movements of pedestrians and cyclists), along with the associated conflict points are illustrated for the MUT and QR, and compared to the current situation in Figure 33, Table 22, and Figure 34. The vehicle-vehicle conflict types determined in this study are classified in three categories: crossing, merging, or diverging conflict points. Additionally, the vehicle-cyclist/pedestrian conflict points are taken into account as well.

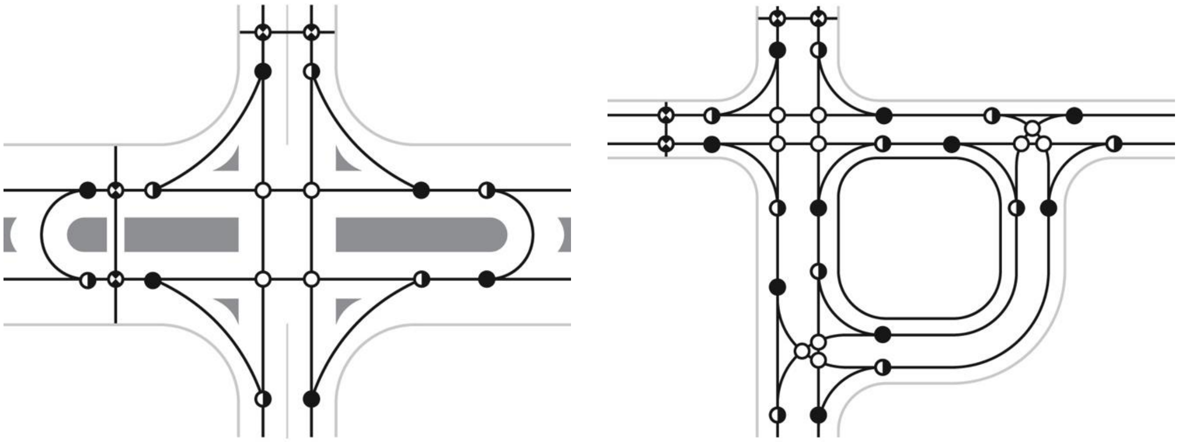


Figure 33 Left: conflict points on the MUT. Right: conflict points on the QR. See, Table 22 for additional description.

Table 22 Number of conflicts of vehicles, pedestrians, and cyclists on the MUT and QR, compared to the current situation.

Symbol	Conflict type	Number of conflict points		
		Current (reference) location 1	Median U-Turn	Quadrant Roadway
	Crossing	16	4	10
	Merging	8	6	10
	Diverging	8	6	10
	Vehicle-Cyclist/Pedestrian	4	4	4

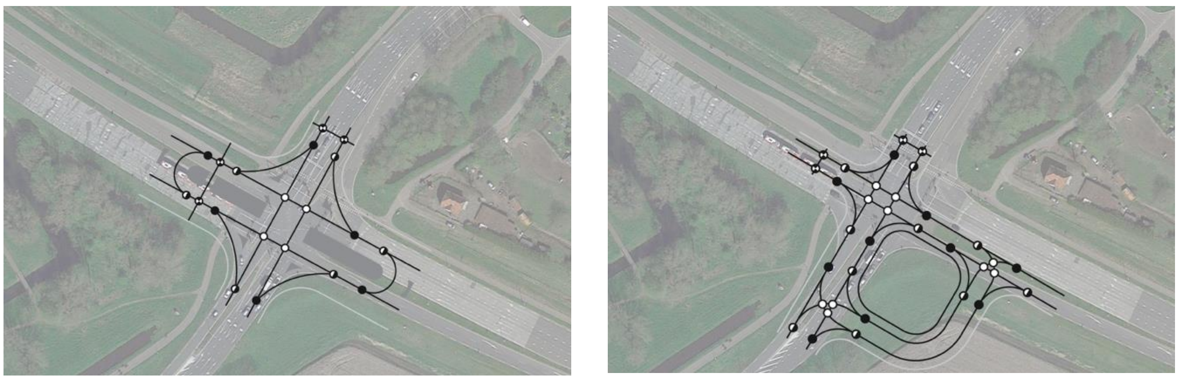


Figure 34 Conflict points plotted on location 1 (not on scale). Left: MUT. Right: QR

What can be observed is that the MUT and the QR reduced the number of conflict points, especially crossing conflict points. As explained before, crossing conflict points, where vehicles are moving in different directions, are associated with more severe crashes than the other two mentioned conflict types. This reduction indicates an improvement of the traffic safety over the current situation.

On the other hand, the number of merging and diverging conflict points for the QR increased. Whether this design improves the traffic safety, can be interpreted in two ways. When converting the traditional intersection to a QR, the number of conflicts is spread out over the three intersections and slightly reduced as well. When interpreted this way, the QR provides an improved traffic safety. Contrarily, the increase in the number of intersections also mean that traffic must cross multiple intersections. As a result, traffic safety might get deteriorated. Hence, more safety measures must be determined to make a statement regarding the impact of the QR on traffic safety.

Time-To-Collision (TTC)

The time-to-collision was calculated for both the current (reference) situation, and the situation where the MUT and QR is applied. The threshold value of 1.5 was applied to only take account of possible severe conflicts. The results are shown below.

Table 23 TTC for the MUT and QR, compared to the current situation

TTC	Number of rear-end conflicts
Current (reference) situation	7877
MUT	5544
QR	6648

It was shown earlier that the number of conflict points reduced, compared to the current situation. Unfortunately, manually determining the exact number of conflicts for crossing, merging, and diverging conflicts during a peak hour was not possible. On the other hand, the number of rear-end conflicts was able to be determined. These conflicts were determined for this safety measure. For the MUT, a reduction, and thus an improvement, of nearly 30% is observed regarding the number of severe rear-end conflicts.

For the QR, it can be argued whether adding two more intersections to the locations might negatively influence the traffic safety. However, the QR design increased the overall capacity with the connector road being added to the location. With left-turns being rerouted, there is a lower volume of traffic using the main intersection. As a result, there is more space between vehicles, reducing the number of potential severe conflicts. In this case, the QR involves approximately 15% less severe rear-end conflicts.

Post-Encroachment-Time (PET)

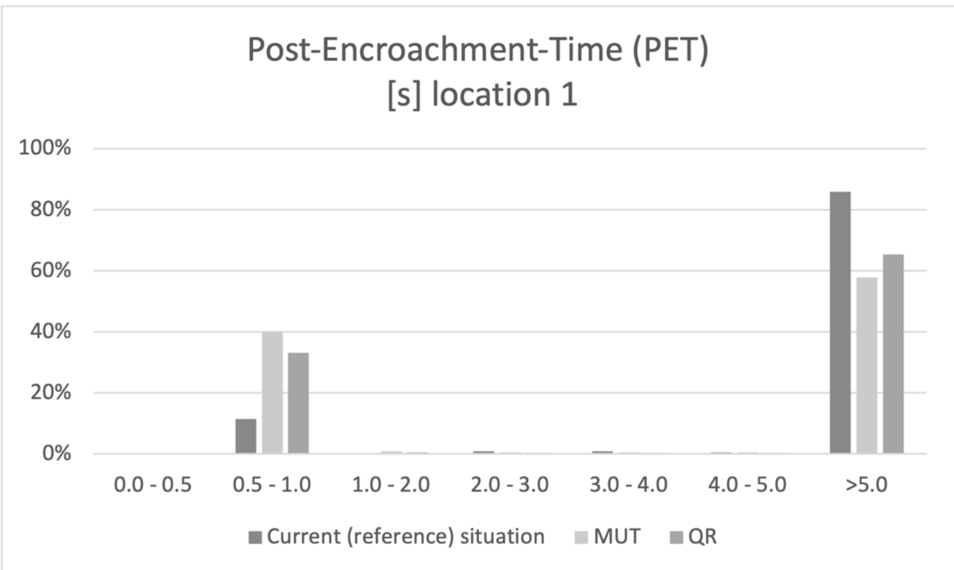


Figure 35 PET values of the MUT and QR, compared with the current situation

As can be observed in Figure 35, many data points have small comparable values, then another part of the data has very large values. As a result, a box plot is not able to display valuable information because it is not intended to handle this type of data. That is why it was decided to use bar charts instead.

Unlike the TTC measure, for the PET a decrease in traffic safety is observed for both the MUT and QR. The PET calculates the time difference between consecutive conflicting vehicles. One of the main differences compared to the current situation is the addition of the U-Turns. For the MUT, as can be seen in Figure 23, the software does not allow (the curvature of the vehicle trajectories on) the U-Turns to be modelled realistically in terms of geometry. This may be why the results show a negative impact on traffic safety.

For the QR, when looking at the number of conflicts, the amount slightly reduces, and that due to the rerouting, the conflict points are spread out over the three intersections. The transition from a traditional intersection to a QR involves adding these two more intersections to the location. Nonetheless, the results show that the number of near misses increased with the QR. Thus, this safety measure indicates that the traffic safety on the QR does not improve over the current situation.

Deceleration rate (MaxD)

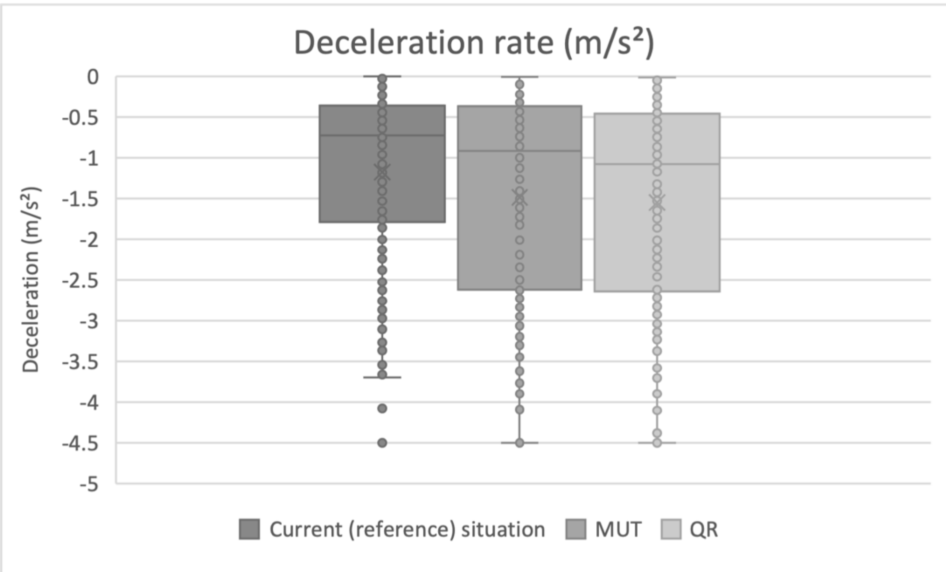


Figure 36 MaxD values of the MUT and QR, compared with the current situation

Study where various deceleration events are analyzed, indicate that the mean deceleration rates vary between -2.2 m/s^2 to -5.9 m/s^2 when approaching an intersection (El-Shawarby et al., 2007). The figure shows that most traffic had deceleration rates around -1. These were situations where the vehicles decelerated just a little bit, but was not meant to stop the vehicle. The remaining data show that no vehicle had to decelerate harder than -5.9 m/s^2. Nonetheless, the boxes of the unconventional designs do appear larger, meaning that there are more vehicles who decelerated a little harder, compared to the current situation. All in all, despite the larger boxes, no extreme deceleration rates (thus, acceptable deceleration rates) were observed.

Speed differentials (DeltaS)

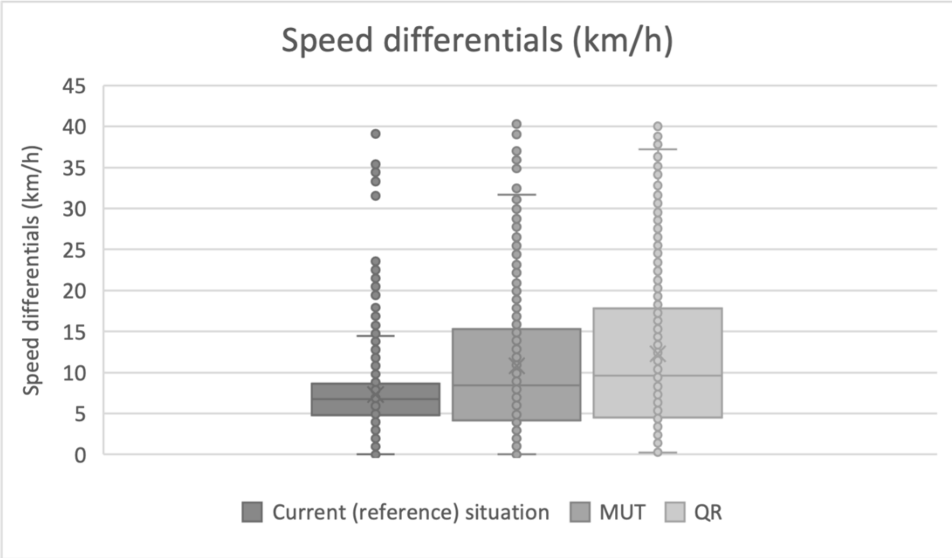


Figure 37 DeltaS values of the MUT and QR, compared with the current situation

The difference in speed between consecutive vehicles was determined. In this case, the lower the speed differences, the larger the homogeneity. This implies a safer traffic situation (SWOV, 2018a). The current (reference) situation has the smallest differences in speeds between consecutive vehicles. The MUT has a larger box, but with the median close to the current (reference) situation. As certain directions have to make an extra stop at U-Turns, the speed differences increase. The figure above shows an increase of 25% for the MUT.

On the other hand, with the QR, the boxes are even larger meaning larger variations in speed differences were observed. Despite this, the median of the QR is approximately 10 (42% increase, compared to the current situation), close to the medians of the other designs. These variations can be explained due to the fact that there are multiple intersections present at the location. As a result, vehicles have to accelerate/decelerate more, creating the larger differences in speeds.

Impact on surroundings

A full reconstruction of the intersection is not necessary with the MUT. Nonetheless, as left-turning lanes were removed in the model, this intersection design was able to be built a little more compact, compared to a traditional intersection. Further, Figure 23 shows that the U-Turns do not look realistic, as it does not show how much space the U-Turn requires. It is not possible to visually model the U-Turn, however, by allocating extra red times to the signals, the time to make U-Turn was taken into account. Further, the signal controller settings (Figure 24) show that there is an overlap with right turning vehicles and slow traffic. It is allowed to design with these overlaps, but it can make the traffic situation less safe.

Generally, the QR is considered on locations where the connector road already exists, just not functions as part of a QR. In this situation there was no connector road, thus had to be added. In which quadrant the connector road should be implemented depends on the left-turn demand. Typically, the direction with the highest left-turn demand uses the most direct route, while the longer route is allocated to the direction with the lowest demand. In this case the quadrant was chosen based on the available space. Accordingly, the longest route was assigned to left-turning traffic originating from zone 003 (West), while the shortest route belonged to left-turning traffic from zone 002 (East). To build the connector road, some property needs to be purchased in order to realize this design. However, this would only apply in this specific situation. The QR can be used in situations where its connector road already exists at a location, thus, without the excessive use of space and high costs.

6.6.3. Location 2 - Setup

Two unconventional designs are modelled at the second location. These are, the Diverging Diamond Interchange (DDI) and the Single-Point Urban Interchange (SPUI). This subsection describes first both designs, consisting of the adjustments that are made, and their signals configuration. Hereafter, the traffic model results are discussed, for each performance indicator and surrogate safety measure. Lastly, the impact of each design on their surroundings is briefly explained.

Diverging Diamond Interchange (DDI)

The DDI was built on the second location with the existing Parclo interchange. Compared to the current location, the following modifications were made:

- The two intersections were modified to function as part of the DDI;
- The number of lanes on the viaduct was decreased from 3x3 to 2x2;
- The number of sorting lanes before the crossovers was decreased as well from 3-5 lanes to only 2;
- The freeway ramps were designed differently, compared to the current situation;
- Traffic signals were adjusted at the crossovers.

Accordingly, the model looks as follows:

Figure 38 Diverging Diamond Interchange alternative in PARAMICS

Signals configuration

The signals of the crossovers consist both of two phases. Additionally, the vehicle-actuated signals were used, to further improve the efficiency of the traffic flow. Report by Hughes et al. (2010) suggests several variations for the design of the signals. From this, the most suitable signal configuration was chosen. This is depicted below.

Table 24 Signal phasing scheme western crossover DDI

DDI West	Phases	
	1	2
Min green	15.0	4.0
Max green	30.0	20.0
Amber	3.0	3.0
All red	0.0	0.0
Ped walk	0.0	0.0
Ped clearance	0.0	0.0

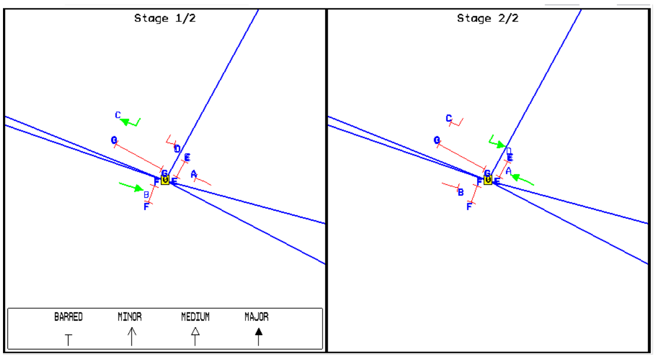


Figure 39 Phasing plan western crossover DDI

Table 25 Signal phasing scheme eastern crossover DDI

DDI East	Phases	
	1	2
Min green	4.0	15.0
Max green	20.0	30.0
Amber	3.0	3.0
All red	0.0	0.0
Ped walk	0.0	0.0
Ped clearance	0.0	0.0

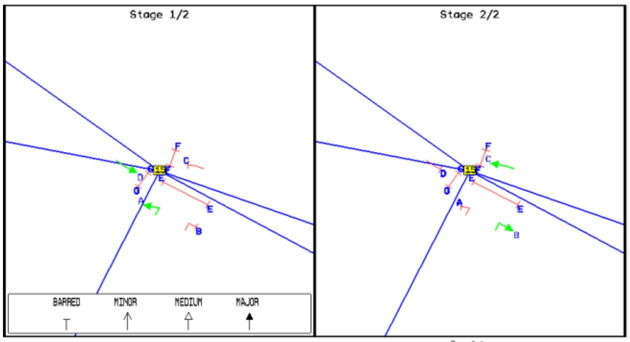


Figure 40 Phasing plan eastern crossover DDI

Single-Point Urban Interchange (SPUI)

The SPUI was also built on the second location with the existing Parclo interchange. Compared to the current location, the following modifications were made:

- The intersections and the viaduct were replaced by one intersection platform;
- The number of sorting lanes before the intersection was decreased from 3-5 lanes to 3;
- The freeway ramps were designed differently, compared to the current situation;
- Traffic signals were adjusted at the intersection.

Accordingly, the model looks as follows:

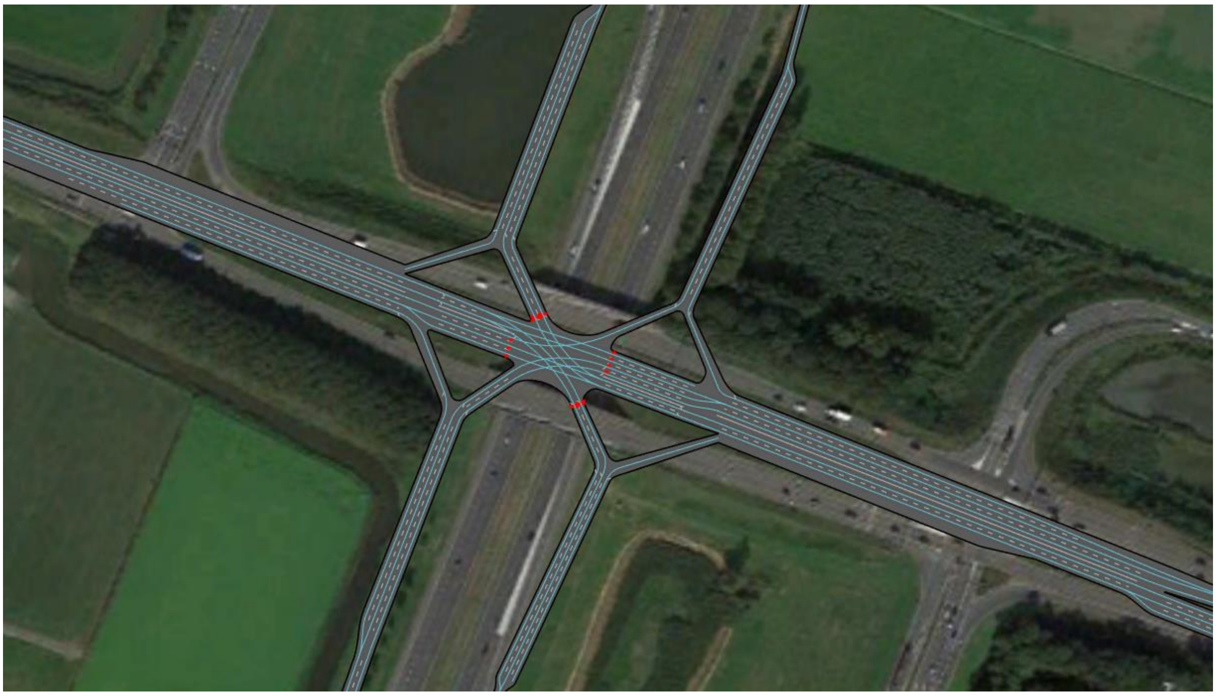


Figure 41 Single-Point Urban Interchange alternative in PARAMICS

Signals configuration

The signals of the intersection platform consist of three phases. Additionally, vehicle-actuated signals were used, to further improve the efficiency of the traffic flow. Report by Hughes et al. (2010) suggests several variations for the design of the signals. From this, the most suitable signal configuration was chosen. This is depicted below.

Table 26 Signal phasing scheme SPUI

SPUI	Phases		
	1	2	3
Min green	4.0	15.0	4.0
Max green	20.0	40.0	20.0
Amber	3.0	3.0	3.0
All red	4.0	4.0	4.0
Ped walk	0.0	0.0	0.0
Ped clearance	0.0	0.0	0.0

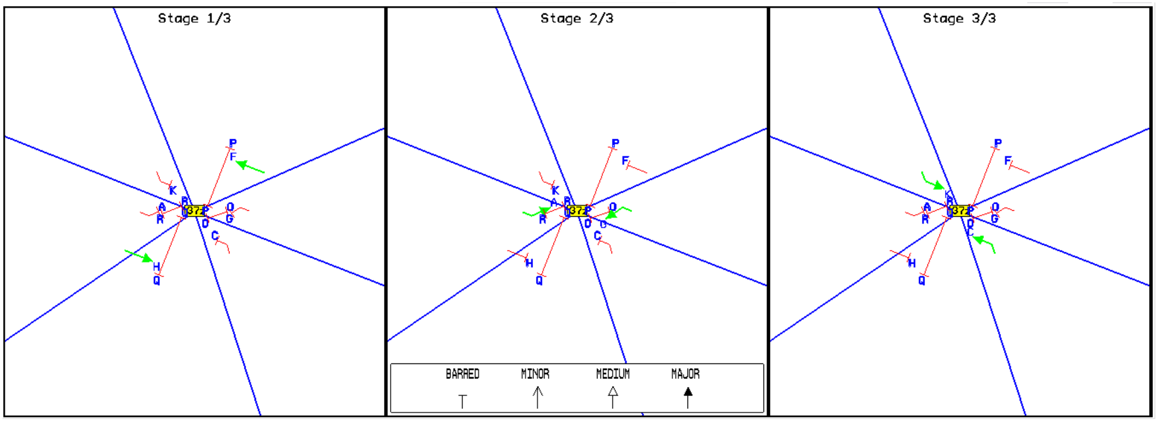


Figure 42 Phasing plan eastern SPUI

6.6.4. Location 2 - Traffic modelling results

Impact on traffic flow

Below, the results of each traffic flow indicator is depicted for the DDI and SPUI. This includes the interpretation of the results, compared to the current situation.

As explained in Section 6.4, the following performance indicators for traffic flow are determined:

5. Travel times (all trips)
6. Travel time differences
7. Vehicle counts
8. Average distance travelled

Travel times (all trips)

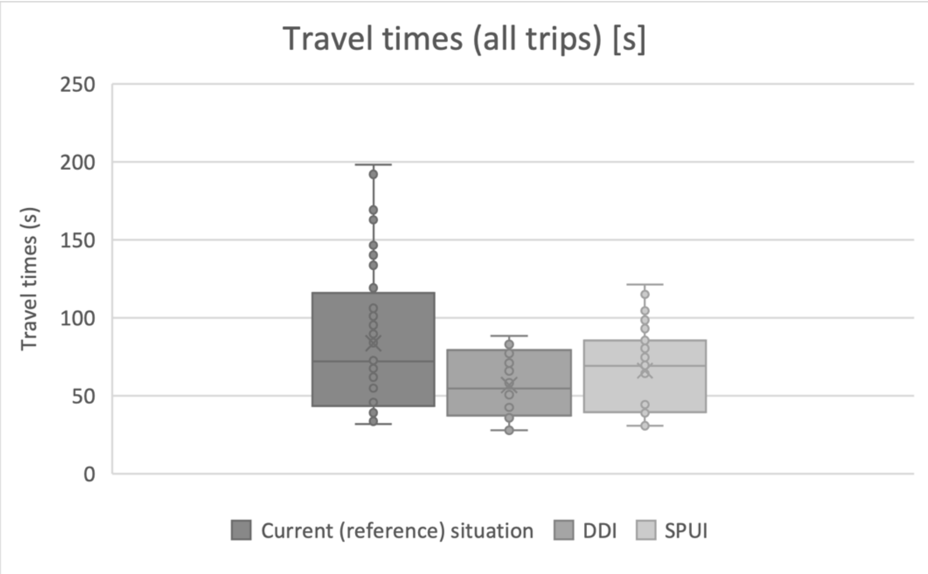


Figure 43 Travel times (all trips) of the DDI and SPUI, compared with the current situation

The average travel times of the whole traffic situation are depicted in Figure 43. A difference can be noticed between the unconventional designs and the current (reference) situation. Generally, both the DDI and SPUI are considered in situations where heavy left-turning vehicles are present. The results show that the unconventional way of the DDI to handle left-turning and through-traffic, improves the travel times over the current (reference) situation with the Parclo interchange. Further, in theory, the SPUI improves the travel times as the number of intersections reduce. This is in line with the results shown in Figure 43. When comparing the medians of all three box plots, an improvement of the DDI and SPUI are observed to be 24% and 4%, respectively.

Travel time differences

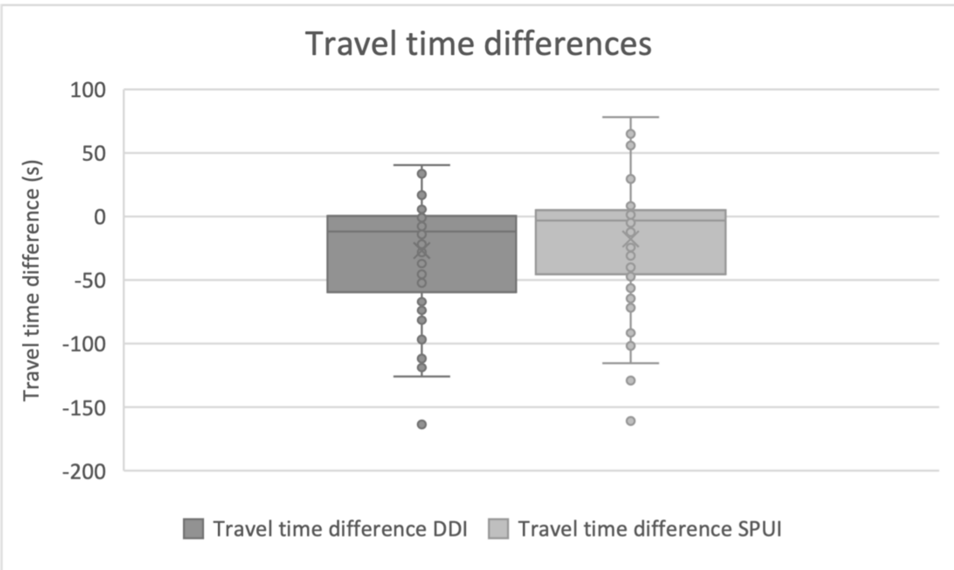


Figure 44 Travel time differences of the DDI and SPUI, compared with the current situation

When the travel times from the new situation with the DDI or SPUI is subtracted from current situation, the travel time differences can be illustrated. These are shown in Figure 44. Most data points appear to be negative, the boxes themselves are also mostly on the negative side. This observation shows that the travel times, compared to the current (reference) situation, improves, but there are several occasions observed that the current (reference) situation performs more efficient than the unconventional designs. When comparing the medians of the box plots, an improvement of nearly 12 seconds is observed for the DDI, while for the SPUI, the travel times improve with approximately 3 seconds.

Vehicle counts

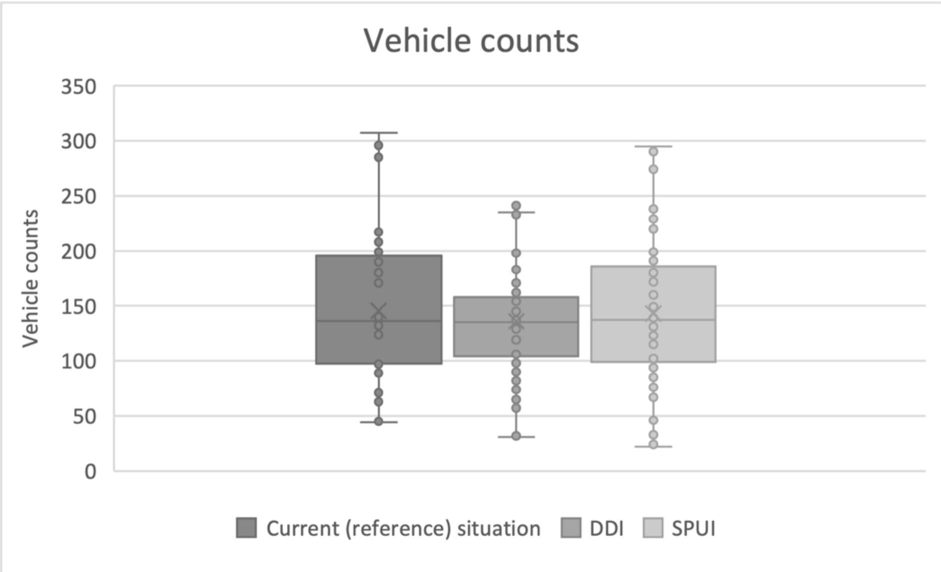


Figure 45 Average vehicle counts on the DDI and SPUI, compared with the current situation

The vehicle counts show how much traffic is present in a certain period. Figure 45 shows that during the simulated peak hour, the DDI allows less vehicles in the area than the current situation. On the other hand, for the SPUI, comparable results are shown, compared to the current (reference) situation. When comparing the medians of each box plots, a decrease of 1% for the DDI and an increase of 1% for the SPUI are observed. These results can mean two things; if the travel times increase, compared to the current situation, it means, together with the increase in vehicle counts, that the network has a small capacity. On the other hand, if the travel times decrease, compared to the current situation, it means, together with the increase in vehicle counts, that the network has a large capacity. In other words, to make a statement on the results for vehicle counts, the results of the travel times and travel time differences also influence this statement.

In case of the DDI, less vehicles are present, while the travel times improved. Therefore, no statement can be made regarding the capacity, as traffic did not have the ability to significantly increase, due to the efficiency in traffic flow. Moreover, the SPUI has an improved travel time, while the number of vehicles at the location remained similar to the current situation. Also here, no statement can be made regarding the capacity. All in all, there is an indication whether the capacity increases for both the DDI and SPUI, as a result of the vehicle counts.

Average distance travelled

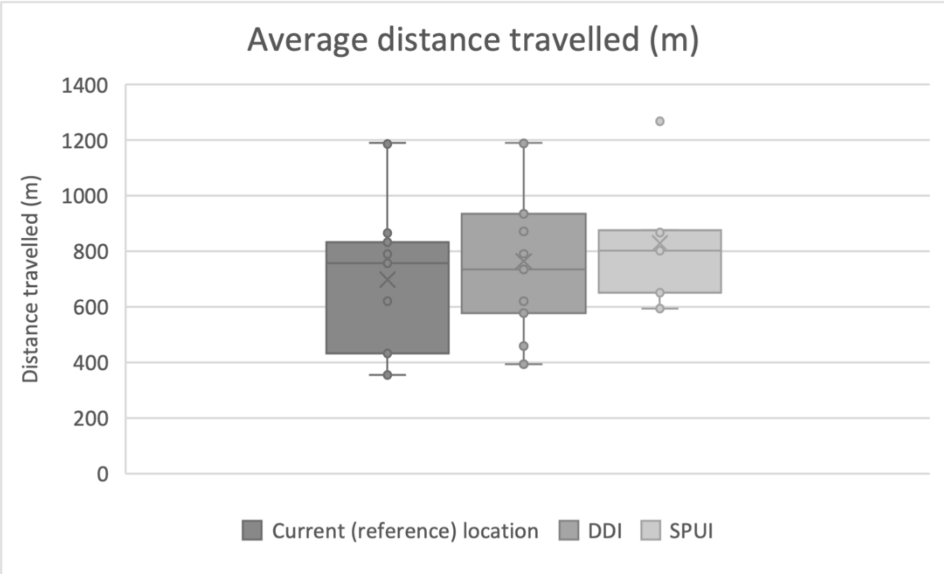


Figure 46 Average distance travelled on the DDI and SPUI, compared with the current situation

When the average distance travelled between the unconventional designs and the current situation is compared, it can be noticed that during the whole simulated peak hour, vehicles on the DDI travel at average similar distances (3% decrease when comparing the medians), compared to the current situation. This is in line with the built traffic model as an attempt was made to keep the number of reconstructions as low as possible by adjusting the current intersections. Generally, the DDI can be built more compact, as indicated in Section 4.3. Further, the SPUI resulted in a smaller box, meaning the results were more significant. Also here, the median is quite similar to the other two designs. A 6% increase is observed, compared to the current situation. Theoretically, no significant differences should be observed as the SPUI does not reroute directions, such as on an MUT. Only the number of intersections decreased. To conclude, based on the average distances travelled, the DDI and SPUI do not have a significant (positive, nor negative) impact on the traffic flow.

Impact on traffic safety

Below, the results of each surrogate safety measure is depicted. This includes the interpretation of the results, compared to the current situation.

As explained in Section 6.5, the following surrogate safety measures are determined:

6. Conflict types
7. Time-To-Collision (TTC)
8. Post-Encroachment-Time (PET)
9. Deceleration rate (MaxD)
10. Speed differentials (DeltaS)

Conflict types

Regarding the possible conflicts, vehicular movements, along with the associated conflict points are illustrated for the DDI and SPUI, and compared to the current situation in Figure 33, Table 22, and Figure 34. The vehicle-vehicle conflict types determined in this study are classified in three categories: crossing, merging, or diverging conflict points.

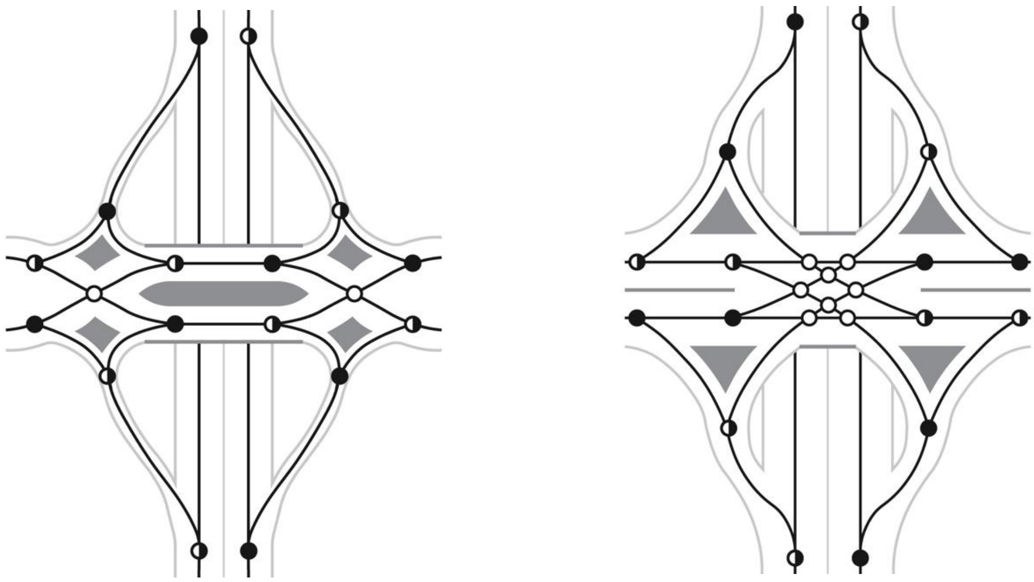


Figure 47 Left: conflict points on the DDI. Right: conflict points on the SPUI. See, Table 22 for additional description.

Table 27 Number of vehicle-vehicle conflicts on the DDI and SPUI, compared to the current situation.

Symbol	Conflict type	Number of conflict points		
		Current (reference) location 2	Diverging Diamond Interchange	Single-Point Urban Interchange
○	Crossing	6	2	8
◐	Merging	8	8	8
●	Diverging	8	8	8

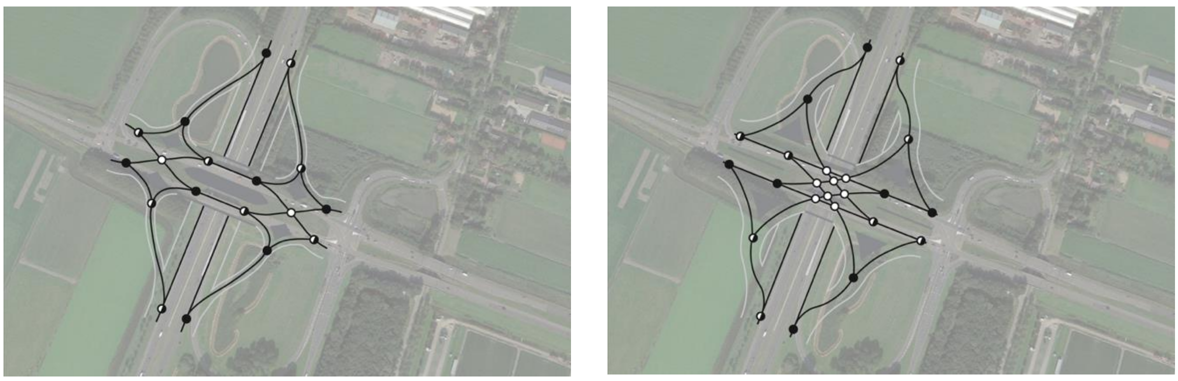


Figure 48 Conflict points plotted on location 2 (not on scale). Left: DDI. Right: SPUI

What can be observed is that the DDI reduces the number of conflict points, especially crossing conflict points. As explained before, crossing conflict points, where vehicles are moving in different directions, are associated with more severe crashes than the other two mentioned conflict types. This reduction indicates an improvement of the traffic safety over the current situation.

Moreover, the advantage of a SPUI, compared to traditional interchanges, is that the number of intersections reduces from two to one intersection. Theoretically, this improves the travel times. Regarding traffic safety, it can be interpreted in two ways. It can be seen as an advantage as now vehicles only cross paths on one location instead of two. The reduction in the number of intersections can also be seen as a downside. What can be observed in the results is that the SPUI slightly increases the number of crossing conflict points. This increase indicates a deterioration of the traffic safety over the current situation.

Time-To-Collision (TTC)

The time-to-collision was calculated for both the current (reference) situation, and the situation where the DDI and SPUI is applied. The threshold value of 1.5 was applied to only take account of possible severe conflicts. The results are shown below.

Table 28 TTC for the DDI and SPUI, compared to the current situation

TTC	Number of rear-end conflicts
Current (reference) situation	8413
DDI	7811
SPUI	8677

It was shown earlier that the number of conflict points reduced with the DDI and slightly increased for the SPUI, compared to the current situation. Unfortunately, manually determining the exact number of conflicts for crossing, merging, and diverging conflicts during a peak hour was not possible. On the other hand, the number of rear-end conflicts was able to be determined. These conflicts were determined for this safety measure. A reduction, and thus an improvement, of 7% is observed regarding the number of severe rear-end conflicts for the DDI. For the SPUI, an increase, and thus a deterioration, of 3% is observed regarding the number of severe rear-end conflicts.

Post-Encroachment-Time (PET)

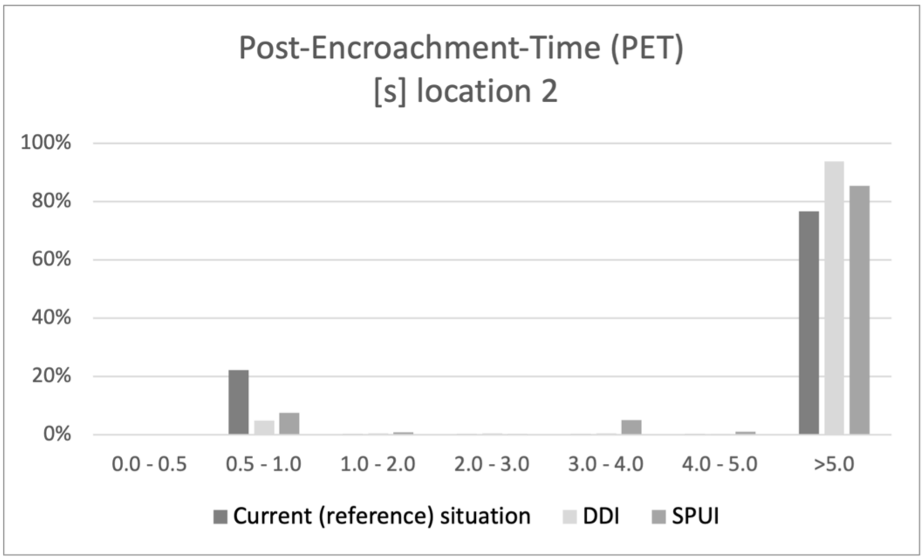


Figure 49 PET values of the DDI and SPUI, compared with the current situation

As can be observed in Figure 49, many data points have small comparable values, then another part of the data has very large values. As a result, a box plot is not able to display valuable information because it is not intended to handle this type of data. That is why it was decided to use bar charts instead.

The minimum post-encroachment-time was calculated for both the current (reference) situation, as the situations where a DDI or SPUI was applied. As mentioned before, all traffic interactions were taken into account. The results in Figure 49 show that most PET values are larger than 5.0, indicating an insignificant chance to collisions. The number of near misses (PET values between 0.5-1.0) reduced with the DDI and SPUI with 17% and 15%, respectively. As the traffic modelling software does simulate crashes, no crashes (PET value 0.0) were observed in the data for both situations.

A shown earlier, the DDI has theoretically less conflict points, compared to the current situation. This means that theoretically, the potential to the number of conflicts reduces. The PET results show that the design also positively influenced the conflicts regarding their severity as the number of near misses reduced. Regarding the SPUI, despite the fact that there are more conflict points on the SPUI (24 conflict points, compared to 22 of a Parclo interchange), the number of near misses reduced. On the other hand, as mentioned before, the number of intersections reduce with the SPUI, which could be interpreted as an improvement regarding traffic safety. It can be assumed that this plays a role in the observed improvement over the current situation.

Deceleration rate (MaxD)

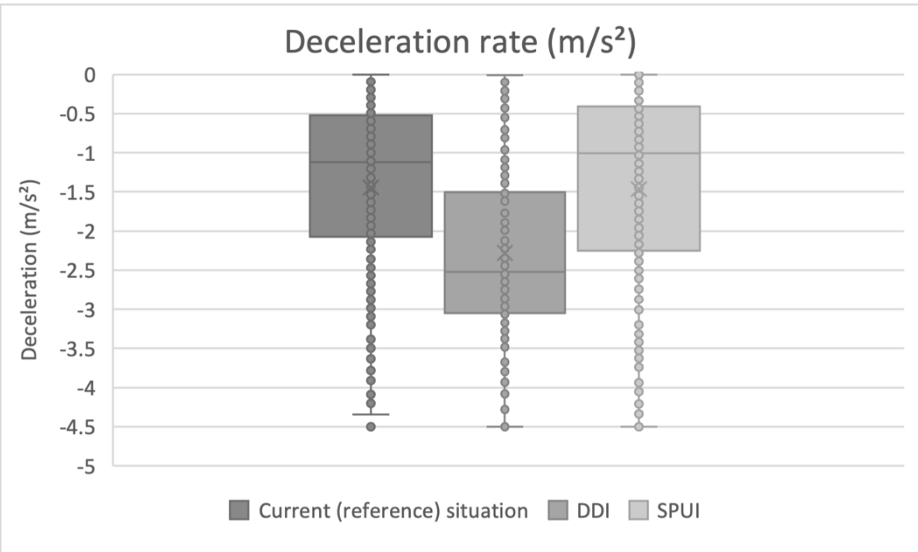


Figure 50 MaxD of the DDI and SPUI, compared with the current situation

Study where various deceleration events are analyzed, indicate that the mean deceleration rates vary between -2.2 m/s^2 to -5.9 m/s^2 when approaching an intersection (El-Shawarby et al., 2007). The figure shows that most traffic has deceleration rates between 0 and -1. These are situations where the vehicles decelerate just a little bit, but not meant to stop the vehicle. The remaining data show that no vehicle has to decelerate harder than -5.9 m/s^2.

Study where various deceleration events are analyzed, indicate that the mean deceleration rates vary between -2.2 m/s^2 to -5.9 m/s^2 when approaching an intersection (El-Shawarby et al., 2007). The figure shows that most traffic had deceleration rates around -1 in the current situation and with the SPUI, while most vehicles on the DDI had a deceleration rate around -2.5. These were situations where the vehicles decelerated just a little bit, but was not meant to stop the vehicle. The remaining data show that no vehicle had to decelerate harder than -5.9 m/s^2. Nonetheless, the boxes of the SPUI and current situation appear to be quite similar, while on average, vehicles decelerated harder on the DDI. All in all, despite the larger boxes, no extreme deceleration rates (thus, acceptable deceleration rates) were observed.

Speed differentials (DeltaS)

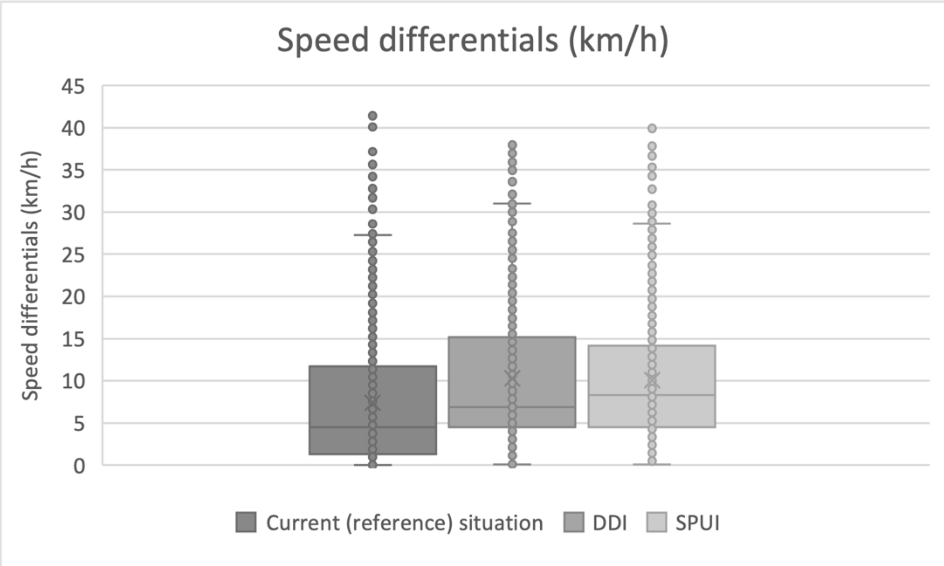


Figure 51 DeltaS of the DDI and SPUI, compared with the current situation

The difference in speed between consecutive vehicles was determined. In this case, the lower the speed differences, the larger the homogeneity. This implies a safer traffic situation (SWOV, 2018a). Figure 51 shows that all three situations had nearly identical speed differentials. What can also be noticed is that most consecutive vehicles had speed differences around 6 km/h, indicating a large homogeneity regarding their speeds. These results show that all three situations ensured high traffic safety, based on this safety measure. When expressing the percentual differences between the medians of each box plot, the DDI and SPUI show an increase of 52% and 85%, respectively.

Impact on surroundings

It was explained before that the DDI is a cost-effective alternative, when comparing it to expanding a conventional interchange or constructing a SPUI. The DDI also requires less lanes, compared to alternatives that handle a similar amount of traffic. At this location, the attempt was made to keep the number of reconstructions as low as possible by adjusting the current intersections.

Further, the intersection platform is an expensive infrastructural component of the SPUI. On the other hand, the number of intersections was reduced this way. The current situation did require a full reconstruction due to the reduction in intersections.

On both the DDI and SPUI, the freeway ramps were designed differently, compared to the current situation with the Parclo interchange. This means that constructional costs increased. In addition, some property must be bought as well to realize these ramps.

6.7. Traffic flow sensitivity analysis

In this subsection a sensitivity analysis was performed regarding the traffic flow, to see how uncertain the output of the traffic models was according to their input. It was chosen to increase the amount of traffic of the whole location. In order to keep the traffic situation realistic, the traffic volume was increased by 5.5% and 10% more traffic. As mentioned before in the introduction of this research, KiM (2020b) expects the traffic volume to increase by at most 5.5% with respect to before the pandemic (2019). To see whether the model can handle more traffic, an increase of 10% was tested as well. Any other aspect of the traffic models, such as the number of lanes and traffic signals, remained the same as before. From the traffic flow indicators, only the travel times were compared to get an indication about how the travel times were influenced when there was an increase in the amount of traffic.

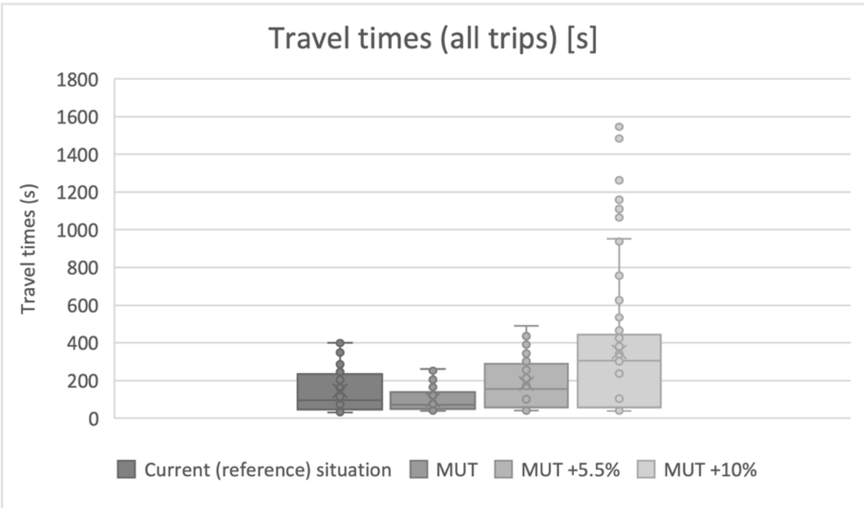


Figure 52 Travel times (all trips) of the MUT with different traffic volumes, compared with the current situation

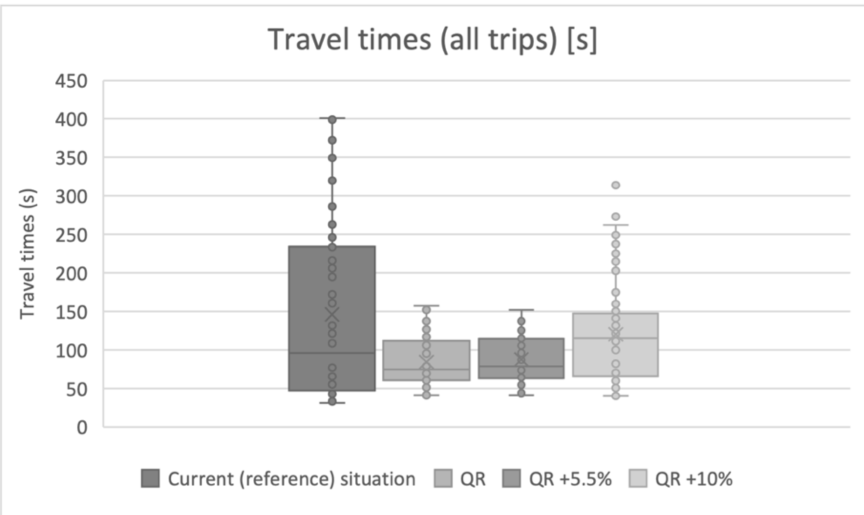


Figure 53 Travel times (all trips) of the QR with different traffic volumes, compared with the current situation

For the first location, the MUT and QR were tested. When looking at the results of the MUT in Figure 52, the increase by 5.5% shows an increase in travel times. These results are comparable to the current situation. Nonetheless, when the traffic volumes are increased by 10%, the travel times significantly increase up to levels that the MUT cannot handle the traffic volume anymore. As can be seen in the figure, many outliers are observed. Due to the absence of a green wave at the U-Turns, lanes intended for traffic that will use the U-turns have a limited capacity. If these large increase in traffic volume does occur in the future, it must be taken into account that these particular lanes could reach their capacity. In the worst case, a traffic jam may occur which can spill back to the main intersection, blocking traffic from other directions.

On the other hand, the QR +5.5% shows similar results, compared to the original QR situation. The difference with QR +10% is more noticeable, however, even when the traffic volumes were increased by 10%, the travel times on the QR remained lower than the current situation with the traditional intersection. The addition of the connector road increased the capacity, leading to a higher efficiency of traffic flow. This in turn positively influenced the travel times experienced on the QR.

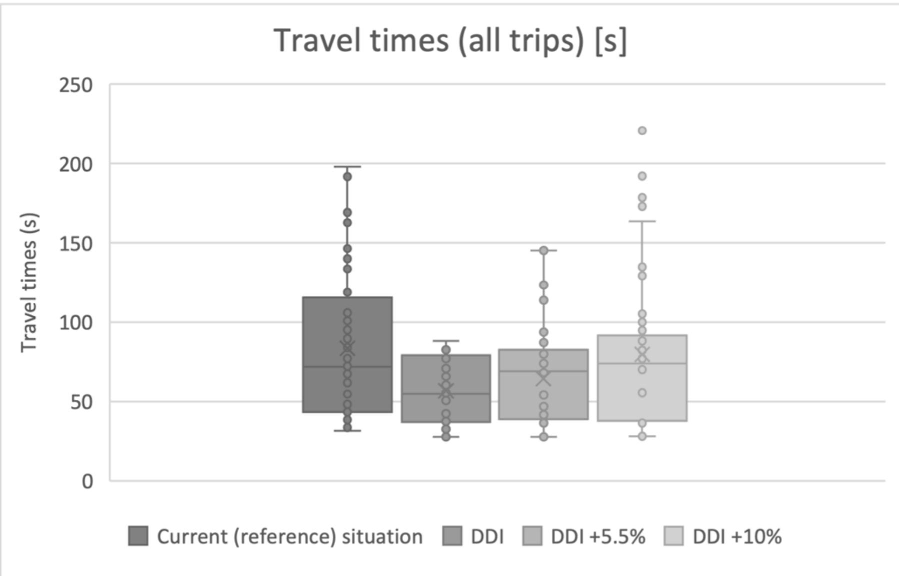


Figure 54 Travel times (all trips) of the DDI with different traffic volumes, compared with the current situation

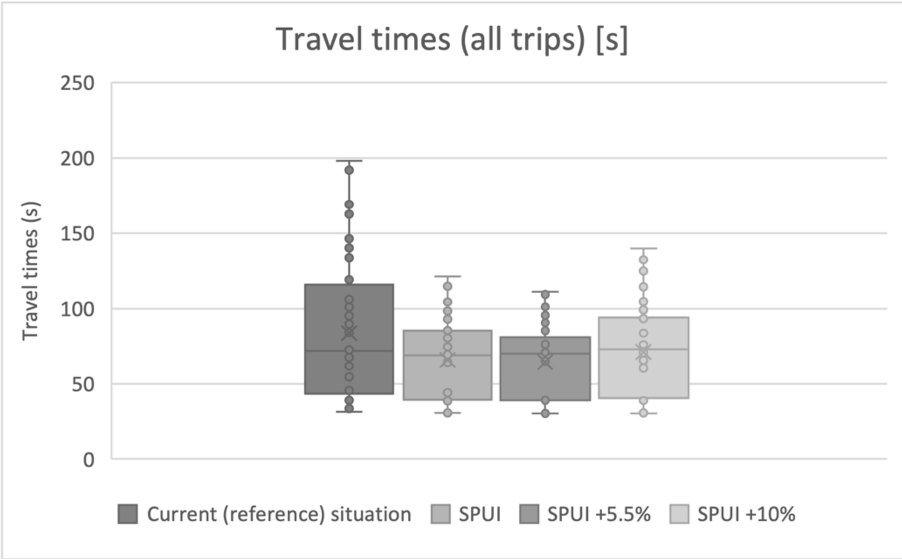


Figure 55 Travel times (all trips) of the SPUI with different traffic volumes, compared with the current situation

For the second location, the DDI and SPUI were tested. When looking at the results of the DDI, the increase by 5.5% shows a small increase in travel times, however, remains on most occasions lower than the current (reference) situation. The increase by 10% shows similar results to the increase by 5.5%, however some outliers are observed. These outliers represent vehicles that faced congestion.

On the other hand, the SPUI +5.5% shows little to no differences, compared to the original SPUI situation. The difference with SPUI +10% is more noticeable, however, even when the traffic volumes were increased by 10%, the travel times on the SPUI remained much lower than the current situation with the Parclo interchange. This shows that, compared to the Parclo interchange and the DDI, the SPUI has a larger capacity.

Overall, this sensitivity analysis regarding the performance indicator for travel times, showed that some deviations in the traffic volumes are possible. An increase of +5.5% is feasible for all designs. However, specifically for the MUT, an increase of +10% would be too much where the potential to congestion significantly increases.

6.8. Traffic safety sensitivity analysis

In this subsection a sensitivity analysis was performed regarding the traffic safety, to see to what extent the number of conflicts were affected when the threshold value changed, compared to the originally used threshold for TTC (1.5). The original threshold value was compared to two other values close to 1.5 that were also mentioned in the study by De Ceunynck (2017). These two values are 1.0 and 3.0. The results are shown below.

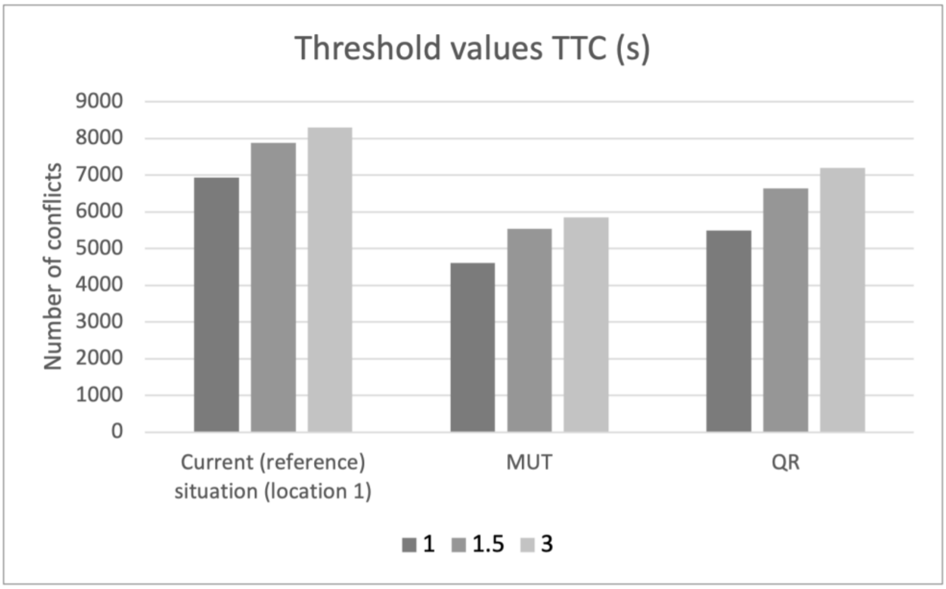


Figure 56 Comparison results of location 1, with different threshold values applied

When looking at the figure above, it can be noticed that the results with all threshold values lie quite close the initially chosen value of 1.5. However, when comparing the results of 1.0 with 3.0, the differences are quite significant. Therefore, using 1.5 does not necessarily mean that it is an incorrect threshold value, but perhaps 1.0 might be a sufficiently high value as well in determining the TTC.

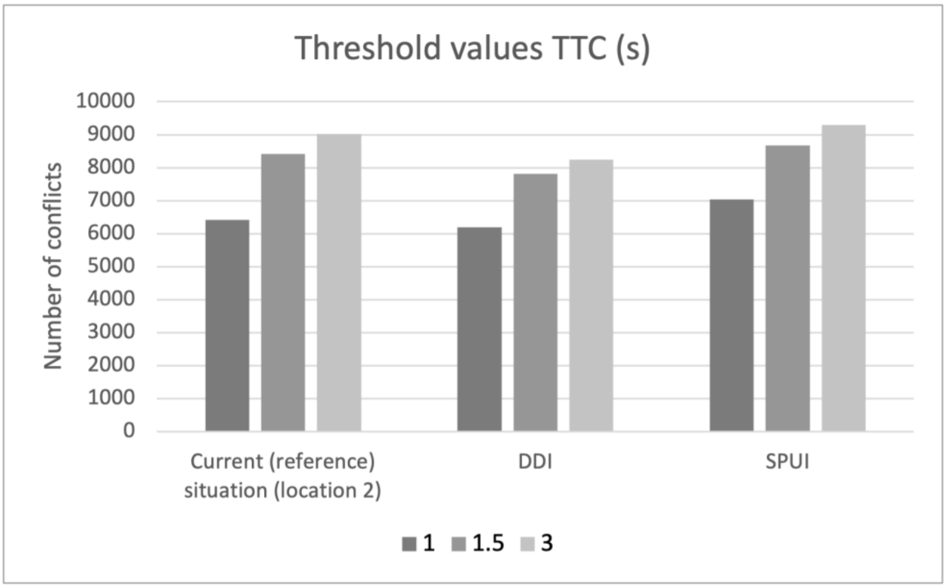


Figure 57 Comparison results of location 2, with different threshold values applied

When looking at the interchanges, the results determined with the threshold value 1.5 lie for all alternatives closer to the results when applying 3.0 as the threshold value. Because these differences are small, this means that 1.5 is a high enough value to use in determining the TTC.

6.9. Implementation of unconventional designs in the Netherlands

As discussed in Section 6.2, a workshop was held at the province Noord-Holland, where, among others, the cases with the four chosen unconventional designs were presented. The highlights of the workshop, including all the slides of the presentation, can be found in Appendix F. It must be noted that the workshop was held in Dutch.

Each design was rated by the experts and professionals. When a design was rated positively, a follow-up question was asked. This question corresponds to the fourth sub question of this study. It was asked, if results from this research would show that a design has a lot of potential in the Netherlands, what are then the next steps you have to take in order to actually build the design? Also, to get the design in the CROW guidelines.
The experts replied by saying “just do it”. It was mentioned that some small studies are necessary on beforehand, such as traffic psychology to determine how people experience new infrastructural components such as the U-Turn. Other than that, guts are necessary to build such designs, but you might receive political backlash if the design turns out to be a disaster. Further, it was not recommended to worry about adding these concepts to the CROW guidelines, as this might take years. All Dutch innovative designs started as an idea, where the developer created their own guidelines with sketches. After that it was a matter of time to get it added to the CROW guidelines. However, in the meantime, it was recommended to show guts and do build and test these designs on a small scale.

6.10. Conclusions

This chapter covered the traffic models that were built to investigate the potential of the chosen unconventional designs under Dutch circumstances. Also, parts of the workshop held at the province were presented in this chapter. In this section, conclusions are drawn, answering sub question 3 and 4.

Conclusions regarding sub question 3

Two reference locations were chosen in the Netherlands, with one consisting of a traditional intersection with the presence of slow traffic and transit, while the other location consisted of a grade-separated Partial Cloverleaf (Parclo) Interchange. The designs in the current situations were then replaced by the chosen unconventional designs and analyses were performed regarding their impact on traffic flow, traffic safety, and the impact on their surroundings. Accordingly, it became possible to answer the fourth sub question of this research. The question was as follows:

What is the impact of the selected designs on the traffic flow, traffic safety, and on its surroundings under Dutch circumstances?

All in all, the results illustrated that the unconventional designs prove to have benefits in terms of traffic flow and/or traffic safety, compared to their corresponding reference situation. The first investigated design was the MUT. This design was applied at the first location as a replacement for the traditional intersection. The results of the performance indicators showed that there was a significant positive impact on the traffic flow, as a consequence of rerouting left-turns with U-Turns. However, longer distances were travelled on the MUT, caused by the rerouting as well. It must be kept in mind that these detours should not become too large, which could deteriorate the attractiveness to use this design by road users. Regarding traffic safety, only positive results were observed which indicated an improved traffic safety. The MUT also had the least impact on its surroundings. Generally, only the U-Turns needed to be added. Therefore, constructional costs could be saved as a full reconstruction is not needed. Finally, there was an overlap with right turning vehicles and slow traffic in the phasing plan of the signals. It is allowed to design with these overlaps, but it could make the traffic situation less safe.

For the first location, the QR was investigated as well. The QR showed major improvements regarding the traffic flow. This was mainly due to the addition of the connector road, which increased the capacity. Surprisingly, the addition of the connector road did not result in significantly longer distances travelled. The connector road causes left-turns from certain approaches to either have a longer route or a shorter route. Despite the longer route for certain traffic, the QR generally allows shorter distances to be travelled. When looking at the number of conflicts, the amount slightly reduced with the QR, and due to the rerouting, the conflict points were spread out over the three intersections. The transition from a traditional intersection to a QR involved adding these two more intersections to the location. Nonetheless, the results showed worse results, compared to the current (reference) situation. Even though the conflict points were spread out, the addition of two more intersections had a negative impact on traffic safety. Lastly, the QR is usually considered on locations where the connector road already exists, just not functions as part of a QR. This way, constructional costs can be kept very low. At this location, the connector road had to be built. To build the connector road, some property needs to be purchased in order to realize this design.

Thirdly the DDI. This design was applied at the second location as a replacement for the Parclo interchange. Results of all the performance indicators showed that the unconventional way of the DDI to handle left-turning and through-traffic, improved the traffic flow over the current (reference) situation. Regarding traffic safety, the DDI showed significant improvements over the current situation in terms of TTC and PET. Only the results of the deceleration rates showed some deterioration, compared to the Parclo interchange. Finally, an attempt was made to build the traffic model in such a way that the number of reconstructions at the location remained as low as possible by adjusting the current intersections. On the other hand, the freeway ramps were designed differently, compared to the current situation. This means that constructional costs increased. In addition, some property must be purchased as well to realize these ramps.

The SPUI was considered as the least attractive interchange to be built at the specific reference location. This design needed the largest reconstruction as the number of intersections reduced and the highway ramps were dimensioned differently as well. Further, the SPUI performed better than the currently built Parclo interchange in terms of traffic flow. Regarding traffic safety, the results were comparable to the Parclo interchange. Sometimes a small deterioration was observed, as well as small improvements.

By way of conclusion, based on the results explored above, it was shown that under Dutch circumstances, the unconventional designs can provide major benefits in terms of traffic flow, traffic safety, and/or the impacts on their surroundings. It must be noted that each design has its own shortcomings, however, none of the designs performed significantly worse based on all three aspects. Hence, there was no necessity to drop certain designs.

Conclusions regarding sub question 4

Furthermore, the fourth sub question can be answered as well, based on the workshop held at the province Noord-Holland. The experts indicated that customization is important, meaning that these innovative designs might not have many use cases in the province, however, on locations where these designs can be built (i.e., locations with the right amount of traffic from certain driving directions), they can have a large positive effect on the traffic situation in terms of improving the traffic flow, as well as the traffic safety, while remaining a compact design. The question was as follows:

What are the steps that need to be taken in order to introduce such new designs to the Dutch roads?

The experts replied by saying “just do it”. It was mentioned that some small studies are necessary on beforehand, such as traffic psychology, to determine how people respond to new infrastructural components such as the U-Turn. Other than that, guts are necessary to build such designs, but you might receive political backlash if the design turns out to be a disaster. Further, it was not recommended to worry about adding these concepts to the CROW guidelines, as this might take years. However, in the meantime, it was recommended to show guts and do build and test these designs on a small scale.

7
Discussion

This chapter presents a comparison between the findings of this study, and the literature on the types of unconventional intersections and interchanges. Further, limitations and assumptions that are made while conducting the research that influence the validity of the conclusions are described as well. This includes a reflection of the methodology and the results. Remaining limitations of the presented work are also mentioned. Finally, the scientific and practical relevance of this research shall be presented.

7.1. Comparison research findings, with literature on unconventional designs

This comparison mainly focused on the results from the traffic models, compared to findings from scientific literature regarding unconventional intersections and interchanges. Comparisons are made for the four designs (MUT, QR, DDI and SPUI) in terms of their impact on traffic flow, traffic safety, and their impact on its surroundings.

According to the results of the traffic model for the MUT, it was shown that the MUT performs well in terms of traffic flow and traffic safety, but with a disadvantage that left-turning traffic travel relatively long distances. Results of several studies are in line with the traffic flow results in this study (Tarko et al, 2008; El Esawey & Sayed, 2011; Rahman et al., 2010). Also, regarding traffic safety improvements, a study by Jagannathan (2007) indicates improvements as well for the MUT. Moreover, some other reports mention the improvements in both traffic flow and traffic safety (Virginia Department of Transportation, 2021; Hughes et al., 2008; Wilbur Smith Associates et al., 2008). Additionally, the same report by Virginia Department of Transportation (2021), mentioned that the MUT should be considered when there is a low to moderate left-turn traffic volumes from all approaches. Also this matches the traffic situation of the first (reference) location where the traffic model with the MUT was built. Lastly, when looking at the impact of the MUT on its surroundings, the MUT had a minimal impact, as generally, only the U-Turns needed to be added. Study by Wilbur Smith Associates et al. (2008) confirms this as their study mention that, depending on development in its vicinity, constructional costs can remain low.

For the QR, the traffic model results showed an improvement in traffic flow, but a deterioration in traffic safety. Results regarding the traffic flow are in line with several studies (Tarko et al, 2008; Virginia Department of Transportation, 2021; Hughes et al., 2008; Wilbur Smith Associates et al., 2008). On the other hand, a report by Virginia Department of Transportation (2021) mentions that the traffic safety on a QR improves due to the fact that conflict points are spread out. This is in contrary with the results from the traffic models, as deterioration is caused by the addition of two extra intersections. Lastly, a report by Hughes et al. (2008) claims that the QR is usually considered on locations where the connector road already exists, just not functions as part of a QR. When building the traffic model, a connector road had to be added, resulting in a negative impact on its surroundings. Therefore, no good comparison with the literature can be made.

Regarding the DDI, its traffic model results showed an improvement in traffic flow, and with most surrogate safety measures, an improvement in traffic safety as well. Results of several studies also indicate that the DDI provides benefits in terms of traffic flow (Bared, Edera et al., 2005; Chlewicki, 2011). Further, regarding traffic safety improvements, a study by Claros et al., 2015) focused on the safety aspect of the DDI and concluded that the DDI improves traffic safety. Also this is in line with the results from this study. Moreover, some other reports and studies mention the improvements in both traffic flow and traffic safety (Virginia Department of Transportation, 2021; Hughes et al., 2008; Wilbur Smith Associates et al., 2008; Federal Highway Administration, 2020; Arcadis et al., 2020). Lastly, regarding the impact of the DDI on its surroundings, a report by Hughes et al. (2008) states that the DDI can be built with less lanes, compared to other interchanges that handle the same amount of traffic. However, in the traffic model, a Parclo interchange was converted to a DDI, meaning the highway ramps had to be reconstructed, negatively impacting its surroundings. In other words, these results do not correspond with the literature.

Lastly, the SPUI results from the traffic models showed an improvement in traffic flow. In terms of traffic safety, no significant differences compared to the Parclo interchange from the reference situation were observed. Reports from Virginia Department of Transportation (2021) and Hughes et al. (2008) describe that the SPUI provides benefits in terms of traffic flow, as well as traffic safety, compared to conventional interchange designs. A study by Chlewicki (2011) does this as well, showing the traffic flow improvements over a conventional diamond interchange. Regarding traffic safety, one study was found by Bared, Powell et al. (2015), showing from observed data that the SPUIs were found to be safer than the comparable diamond interchanges for injury/fatality frequencies. These findings are not in line with the results from the traffic models, as no significant differences, compared to the current situation with the Parclo interchange, was found. Lastly, regarding the impact of the DDI on its surroundings, the SPUI is a compact design as the number of intersections reduce from two to one (Hughes et al., 2008). However, in the traffic model, a Parclo interchange was converted to a SPUI, meaning the highway ramps had to be reconstructed. In other words, despite the compactness, a negative impact on its surroundings was observed.

7.2. Research limitations and assumptions

A number of aspects are discussed in this chapter. These include, the presence of subjective elements, the limitations faced in the traffic safety evaluation, and the assumptions and limitations related to the traffic models.

7.2.1. Presence of subjective elements

Beforehand of this research, in total of ten unconventional designs were chosen to be studied. These ten designs were chosen based on how often these are mentioned in various governmental reports and scientific articles. In other words, the amount of information available played a role in determining the ten designs. Strictly speaking, this could be interpreted as a subjective way of choosing the designs.

Further, the number of designs was reduced to two intersections and two interchanges, by using a multi-criteria analysis. The scores are motivated with the help of scientific articles; however, the final score is given by the author of this research. The weight factors of each criterion are determined by the author as well. To reduce the subjectivity, the chosen designs were presented to the province to receive expert judgement on these innovative types of intersections and interchanges.

7.2.2. Limitations traffic safety evaluation

Sustainable Safety principles are used, in combination with the Dutch and American design guidelines. Sustainable Safety principles focus on designing the traffic environment in such a way that no serious accidents can occur. If an accident does occur, then severe outcomes remain limited (SWOV, 2018a). These principles mainly relate to road sections, which also include intersections and interchanges. However, the limitation of this evaluation method is that infrastructural components such as the U-Turns are specifically not taken into account.

The designs, part of this evaluation, are located in the United States. To determine the dimensions of the infrastructural aspects, such as the lanes, Google Maps is used to measure these. It can be argued how reliable these measurements are, thus certain deviations must be taken into account.

7.2.3. Assumptions and limitations traffic models

Below, the geographical assumptions to build the traffic models are discussed. The limitations of the software PARAMICS are noted as well, along with its consequences for this research.

Geographical assumptions

Many assumptions were made regarding the traffic models. These assumptions are also discussed in the associated Chapter 6. Below, they are described again.

Firstly, the intersection at location 1 is currently being reconstructed. As traffic data is not available of this new situation yet, the old situation was used for this study. On this South side, a house is located. Regarding the Quadrant Roadway (QR), it is difficult to use this design with the presence of this house. Therefore, for this study it is assumed that the house does not exist, and that permission is granted to build the connector road of the QR on the green plain in the Southeast area. Lastly, the intersection located on the Nord side was disregarded as well. This intersection exchanges traffic from residential areas nearby but is not expected to significantly affect the traffic flow of the main intersection this study focuses on. Thus, to avoid making the model unnecessarily complex, it is disregarded.

Two critical assumptions are made for the second location. The road section on the North of the Eastern intersection that leads to an urban area, causes the unconventional designs to be modified in a way that they do not function anymore as intended. To avoid this issue, the assumption was made that traffic going/coming from the northern road section gets rerouted elsewhere. This northern road can then be disregarded, and the interchange shall then consist of two three-legged intersections. To keep the comparisons between designs fair, this northern road section was disregarded from all, including the current situation. At the second location, the Diverging Diamond Interchange (DDI) and the Single-Point Urban Interchange (SPUI) are applied. The DDI, as well as the SPUI, are both designs that are considered at locations where heavy left-turning vehicles are located. This is not the case for this location. During the workshop at the province, it was recommended to build traffic models for the location N242-N508 instead. However, due to the lack of time it was not possible to build these models during the remaining research period. Instead, it was chosen to increase all the left-turning OD-routes by 50% for the traffic models of the initially used location. By increasing the traffic volumes for those routes by 50%, the same number of lanes was able to be maintained, without the presence of very large congestions in the traffic model of the second (reference) location.

Software limitations

PARAMICS software is used to build the traffic models. With certain models, green waves are necessary when multiple intersections are present in the road network. Due to the complexity of applying green waves into the model, a more pragmatic approach was chosen by turning the fixed signals into vehicle-actuated signals. It must be noted that this might not work as efficient as green waves themselves, which affects the results of the presented work.

Another limitation of using PARAMICS as the software to build traffic models is that the output of PARAMICS cannot be used with the SSAM software tool to determine the surrogate safety measures. Months before starting with the traffic models, it was mentioned in literature that PARAMICS Quadstone could export trajectory files (.trj). Specifically, it must be noted that in this research PARAMICS Discovery is used. It eventually turned out that both software packages, despite their similar names, are different products, provided by two different companies. For this reason, the safety measures had to be manually determined through Excel. This had certain limitations as it became practically impossible to determine the number of conflicts per conflict type (crossing, merging, and diverging conflict types). This is the main reason why only the rear-end conflicts were determined. Moreover, this manual determination of the results is also prone to calculation errors. These are aspects that have to be kept in mind when making statements regarding the traffic model results.

7.3. Contribution of presented research

This research aims to contribute to creating attention for unconventional solutions for intersections and interchanges that have the potential to improve the traffic flow and traffic safety in the Netherlands. The following contributions are provided:

Traffic models study of unconventional (American) designs under Dutch circumstances

No scientific research was found focusing on how unconventional (American) designs perform under Dutch circumstances. This study includes Dutch locations where Dutch traffic volumes are present. Additionally, one of the locations includes the presence of pedestrians, cyclists, and transit, to resemble typical Dutch circumstances. The results of these traffic models give an indication of how these American designs perform in the Netherlands in terms of traffic flow, traffic safety, and their impact on its surroundings.

Methodology to assess American designs with the Dutch Sustainable Safety principles

A desk investigation is constructed according to the Sustainable Safety principles. For this desk investigation, criteria of the Sustainable Safety principles are rephrased to questions which only the author of this study has given answer to for each of the designs, based on observations made through Google Maps/Street View. This did not exist yet, and also includes the comparisons between the American and Dutch guidelines for road design.

Introducing new infrastructural designs to the Dutch roads

The workshop held at the province was found to be valuable for determining what the following steps would be in order to actually build new designs in the Netherlands. It was told to “just” build them, meaning that it is not necessary to get these designs in the Dutch design guidelines before actually building them. However, it is mentioned that some small studies are necessary on beforehand, such as traffic psychology to determine how people experience new infrastructural components such as the U-Turn. Other than that, guts are necessary to build such designs, but you might receive political backlash if the design turns out to be a disaster.

8
Conclusions and recommendations

This chapter includes conclusions drawn for the main research question and the sub questions. Hereafter, recommendations are made for further research.

8.1. Conclusions

This study aimed at investigating whether unconventional designs, consisting of intersections and interchanges, have the potential to improve the traffic flow and traffic safety, under typical Dutch circumstances. This not only includes Dutch road characteristics and traffic volumes, but also includes the presence of pedestrians, cyclists, and public transport. The main research question is defined as follows:

What is the potential of unconventional intersections & interchanges to improve traffic flow and traffic safety in the Netherlands?

Four designs were determined, consisting of two intersections and two interchanges, that were then extensively researched. These four designs are the following:

Intersection designs:

1. Median U-Turn (MUT)
2. Quadrant Roadway (QR)

Interchange designs:

3. Diverging Diamond Interchange (DDI)
4. Single-Point Urban Interchange (SPUI)

It turned out that based on Sustainable Safety principles and design guidelines, only a small number of plausible adjustments in the width of the lanes are needed to adopt American unconventional designs in the Netherlands. These four designs also made a positive impression on the experts and professionals of the province Noord-Holland. Further, all four designs have shown positive results through traffic models, in terms of their impact on traffic flow, traffic safety, and/or impact on its surroundings, under Dutch circumstances.

Furthermore, as mentioned during the workshop at the province, the efficient use of space of unconventional designs is a great benefit, especially with the increasing urbanization in the Netherlands. Additionally, customization is important regarding these innovative designs, meaning that they might not have many use cases in the province, however, on locations where these designs can be built (i.e., locations with the right amount of traffic from certain driving directions), they can have a large positive effect on the traffic situation in terms of improving the traffic flow, as well as the traffic safety, while remaining a compact design. By way of conclusion, based on all the findings explored above, it has been proven that the unconventional designs for intersections and interchanges have great potential to improve the traffic flow and traffic safety in the Netherlands. However, it must be noted that some more studies are necessary before these designs can actually be built in the Netherlands. An example is a traffic psychology study to determine how road users experience unconventional designs. More about the recommendations can be read in the next section.

8.2. Recommendations for further research

This research aims to contribute to creating attention for unconventional solutions for intersections and interchanges that have the potential to improve the traffic flow and traffic safety in the Netherlands. However, some additional work is necessary that complement this research, before these designs could actually be built in the Netherlands. Based on the limitations mentioned in the previous chapter, and some additional topics not covered in this study, several recommendations for future research are made. These are as follows:

Bowtie and Restricted Crossing U-Turn (RCUT)

The results of the traffic models have shown that the MUT has a great potential to improve the traffic flow and traffic safety. Hence, it is recommended to do some further research on designs that are similar to the MUT. Firstly, the Bowtie intersection. This is a type of intersection that is exactly the same as the MUT, but the U-Turns are replaced by roundabouts. Secondly, the RCUT, which is also very similar to the MUT, but where through movements from the side street also make use of the U-Turns. The RCUT was part of the ten designs this study initially started with. Reference is made to Appendix A, where the RCUT is explained more in detail.

Using SSAM to evaluate surrogate safety measures

The software tool SSAM can be used to determine surrogate safety measures, such as the number of crossing, merging, and diverging conflicts. Due to the incompatibility of the output of PARAMICS with SSAM, this software tool could not be used in this study. Manual calculations had to be made instead, which had its limitations as mentioned in the previous chapter. In order to use SSAM, different software has to be used to build the traffic models, such as VISSIM. Since PARAMICS and VISSIM are both microscopic software packages, they serve the same purpose. Therefore, similar results are to be expected regarding the traffic flow indicators. VISSIM can export trajectory files (.trj) that can be used in SSAM to determine the impact on of the designs on traffic safety more comprehensively.

More focus on slow traffic

Slow traffic (pedestrians and cyclists) was limitedly taken into account in this study. They were taken into account when determining the conflict points of each design. Further, pedestrians and cyclists are only considered in the traffic signal schemes in the traffic models. This means that this study did not focus on how slow traffic experience new designs (i.e., traffic psychology). Moreover, the surrogate safety measures only applied to vehicles. Altogether, a recommendation is made to study traffic situations with the presence of slow traffic more explicitly.

Optimized traffic models

It must be noted that the seed values were not touched in the traffic models, and thus kept random. This means that in each simulation, vehicles enter the network at random times. Moreover, for each design only one simulation was run, while normally ten or more simulations are run. It is therefore recommended to either keep the same seed values for all models, or run multiple simulations per model, to gain more reliable results.

Further, due to the complexity of applying green waves into the traffic models, a more pragmatic approach was chosen by turning the fixed signals into vehicle-actuated signals. It is a good approximation, but a green wave might work a little better. Applying green waves into the traffic models is something that can be done in further research to determine whether there are any differences in terms of efficiency of the traffic flow. It is also possible to go a step further by using smart traffic signals instead, as this is something what the province is doing a lot with lately. Smart traffic signals (iVRI) work traffic-dependently, meaning that the signals and road users can communicate with each other. This in turn makes it possible to allocate green times even more efficiently. A possible recommendation would be to combine the concept of the iVRI, with the unconventional designs in traffic models, and check how the traffic flow and traffic safety gets affected.

Recommendations made by the province for further research

During the workshop held at the province it was mentioned that, when wanting to build these unconventional designs in the Netherlands, some small studies are necessary on beforehand. One study that was mentioned is traffic psychology to determine how road users experience new infrastructural components such as the U-Turn. The results of this study will provide more knowledge about how road safety is affected, based on possible driver confusion.

Moreover, it was mentioned that the surface of the U-Turns might wear out quickly due to the movements, especially caused by heavy vehicles. No studies were found regarding this topic in scientific literature. Hence, it would be an interesting topic for a follow-up study.

Determining quantitative cost estimations

This study has not comprehensively focused on the costs to build the designs. Instead, statements are made whether a design is expensive or not, based on their sizes and use of space. When considering these designs, costs can also play a role in the decision making. A possible (part of a) follow-up study could be doing a cost-benefit analysis for a reference situation, and compare this against other potential alternatives

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A
Summary unconventional designs of intersections and interchanges

On beforehand of this research, a total of ten designs consisting of unconventional American intersections and interchanges were analyzed. After considering the advantages and disadvantages, the number of designs were reduced to two intersections and two interchanges. The complete list is covered in this appendix chapter.

- Intersections:
  - Center Turn Overpass
  - Continuous Green-T
    - Also known as the Seagull Intersection
  - Displaced Left-Turn intersection
    - Also known as the Continuous Flow Intersection
  - Echelon
  - Median U-Turn
    - Also known as the Michigan Left-Turn
  - Quadrant Roadway
  - Restricted Crossing U-Turn
    - Also known as the Superstreet Intersection
- Interchanges:
  - Displaced Left-Turn Interchange
    - Also known as the Continuous Flow Interchange
  - Diverging Diamond Interchange
    - Also known as the Double Crossover Diamond
  - Single-Point Urban Interchange

A1. Intersections

Center Turn Overpass

Figure 58 Conceptual rendering of the Center Turn Overpass.

The Center Turn Overpass (CTO) elevates all left-turn movements from the main intersection with the use of ramps that meet at the center of the intersection. Further, all left-turn vehicles use an acceleration lane to merge with through traffic. So, it's two intersections with one being elevated. Both the intersections are controlled by a two-phase signal and similarly to conventional intersections. At the time this report was prepared, no information was available regarding locations where this design has been applied. This design can be considered in urban and suburban areas when heavy left-turning traffic is present. Furthermore, the left-turning traffic volumes should be similar from all approaches. The CTO has 24 conflict points, consisting of 8 crossing, 8 merging, and 8 diverging conflict points. On the other hand, a conventional intersection has 32 conflict points, consisting of 16 crossing, 8 merging, and 8 diverging conflict points.

On the right an illustration of the CTO is shown indicating the movements. In red the movements are shown on the intersection located at ground level. Vehicles using the intersection on top are indicated in blue.

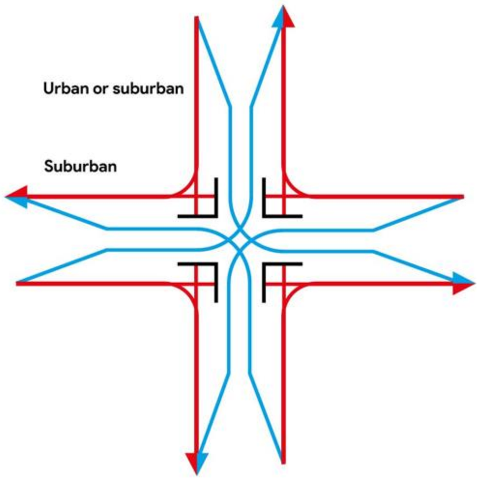


Figure 59 Vehicular movements on a Center Turn Overpass

Advantages (Hughes et al., 2010)

- Both signalized intersections require only two phases
- Consisting of two intersections results in a high capacity. Simultaneously, this should improve the traffic flow
- It is possible to include pedestrian crossings and cycle lanes into the design. These are all positioned at ground level.

Disadvantages

- It is difficult to design if streets are not perpendicular. It would be more beneficial in cities with a grid structure. However, this is not common in the Netherlands.
- High structural costs are involved.
- Additionally, due to the patented design, the costs increase even more.

Continuous Green-T

Figure 60 U.S. 40 (Columbia Pike) at Rivers Edge Road, Columbia, Md.

With the Continuous Green-T (CGT) intersection, the road on top functions as a major street where through going traffic can pass without any interferences. The road of the vehicles for the opposite direction is typically signalized; however, it is possible to be designed without. Furthermore, the vehicles that want to make a left-turn from the side street use a bypass to merge onto the major road. By using a bypass, the load on the intersection reduces and an additional lane on the major road is not necessary anymore. This design can be considered at suburban locations with a T-intersection. Moreover, where the major road has a high traffic volume, while the side street has moderate to low left-turning traffic. The CGT has 9 conflict points, consisting of 3 crossing, 3 merging, and 3 diverging conflict points. The number of conflict points (also per conflict type) is the same as for a conventional T-intersection.

Below, an illustration of the CGT is shown indicating the movements. A distinction in colors (blue and red) is made to indicate the origin of the movements. Physical separations are shown in green for more clarity.

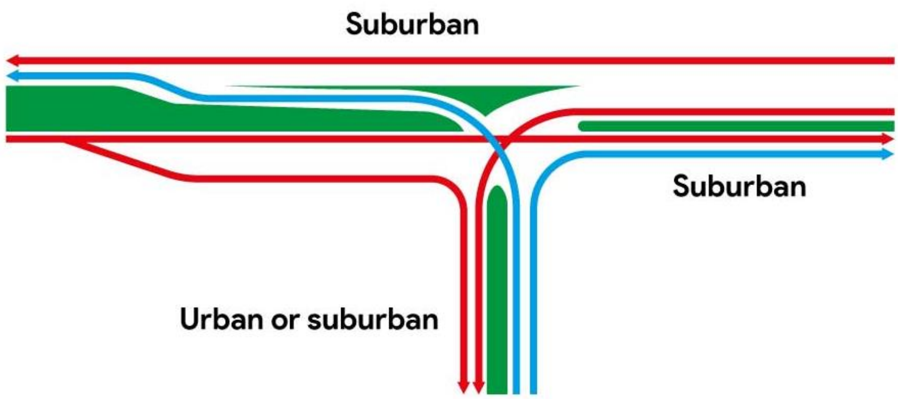


Figure 61 Vehicular movements on a Continuous Green-T

Advantages (Tarko et al., 2008)

- Reduced delay for through traffic on the suburban road in one direction
- Reduced stops for through traffic on the suburban road in one direction
- It is possible to include pedestrian crossings and cycle lanes into the design.

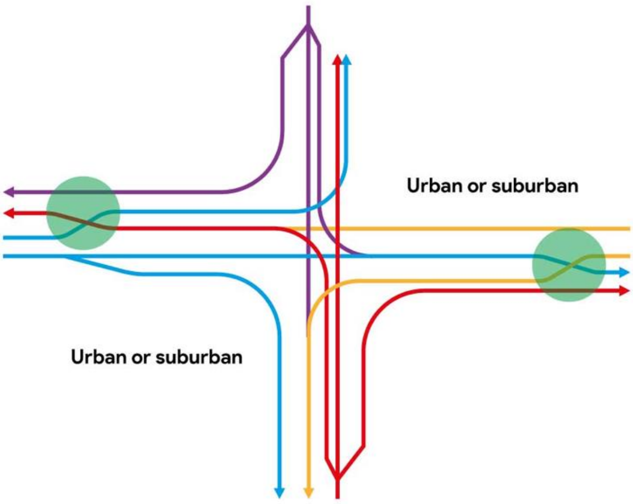
Disadvantages

- The new type of intersection can cause confusion among drivers
- Drivers may ignore the separation between the through lanes
- Pedestrians and cyclists crossing the major road are unprotected by signals
- The number of lane-changing conflicts increase before and after the separation of the through lanes

Displaced Left-Turn Intersection

Figure 62 State Route 741 (N Springboro Pike) at Austin Boulevard, Miamisburg, OH.

The Displaced Left-Turn (DLT) is an intersection where left-turn vehicles use the crossovers to cross to the other side of the road of the opposing through-traffic before arriving at the main intersection. This allows left turns and opposing through movements to move simultaneously through the main intersection, which reduces the number of signal phases and delay. The intersection can be designed as a partial DLT, meaning that there are only crossovers for left turns on the major road. A full DLT is also possible, with crossovers for left turns on both the major and minor roads. The main intersection and crossovers are signalized and synchronized to minimize stops. Additionally, this intersection can also be designed as an interchange (discussed later). This design is considered in urban and suburban areas when there is moderate to heavy traffic volumes in all directions. Also, when heavy left-turning traffic is present. The full DLT has 28 conflict points, consisting of 12 crossing, 8 merging, and 8 diverging conflict points. A partial DLT has 30 conflict points, consisting of 14 crossing, 8 merging, and 8 diverging conflict points. On the other hand, a conventional intersection has 32 conflict points, consisting of 16 crossing, 8 merging, and 8 diverging conflict points.



On the left an illustration of a partial DLT is shown with colored lines indicating the movements and directions. The green circles show the locations where the crossovers are located.

Figure 63 Vehicular movements on a partial Displaced Left-Turn intersection

Advantages (Bruce & Gruner, 2007)

- Less expensive compared to constructing a grade-separated interchange.
- High capacity.
- Requires relatively less time to construct.
- Fewer conflict points compared to a conventional intersection.
- Due to a reduction in delays the traffic flow improves.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- Larger construction compared to a conventional intersection.
- The new type of intersection can cause confusion among road users.
- There are internal conflict points.
- Adding pedestrian crossings and cycle lanes is possible but less convenient compared to a conventional intersection.

Echelon

Figure 64 Conceptual rendering of an echelon.

The Echelon intersection shows similarities with the Center Turn Overpass, but in this case one approach on both roads is elevated. Both intersections of the Echelon are equipped with two-phase signals and work similarly to conventional intersections. This type of intersection is very suitable for use in scenarios where both the intersecting roads have similar traffic volumes. At the time this report was prepared, no information was available regarding locations where this design has been applied. This design can be considered in urban and suburban areas when the traffic volumes are similar from all approaches and heavy traffic volumes are present. The Echelon has 22 conflict points, consisting of 6 crossing, 8 merging, and 8 diverging conflict points. On the other hand, a conventional intersection has 32 conflict points, consisting of 16 crossing, 8 merging, and 8 diverging conflict points.

The illustration on the right shows a simplified version of the Echelon intersection with the vehicular movements and directions. The elevated approaches are indicated with the colors yellow and blue. The intersection at ground level is in red. For clarity reasons not all the vehicular movements are shown of this latter intersection. However, this intersection works similar to a conventional intersection with each direction having its own sorting lane.

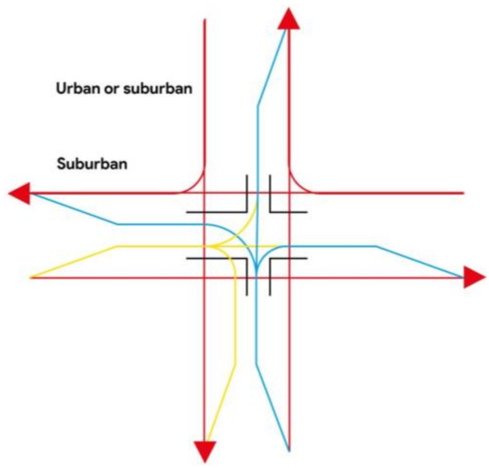


Figure 65 Vehicular movements Echelon intersection

Advantages

- There is a higher road capacity compared to regular at-grade intersections, which also improves the travel time.
- Traffic is metered to assist downstream signals
- The signalized intersections require only two phases.
- A reduced number of conflict points, indicating an improved traffic safety.

Disadvantages

- High structural costs are involved.
- It is an unfamiliar interchange in the Netherlands. Drivers have to get used to it.
- Implementing this interchange is only beneficial when both the crossing roads have a similar traffic volume.
- The main disadvantage is that pedestrians and cyclists are unprotected by signals.
- It is possible to include pedestrian crossings and cycle lanes into the design. However, a staircase or ramp may be required in some locations due to retaining walls or other objects.

Median U-Turn

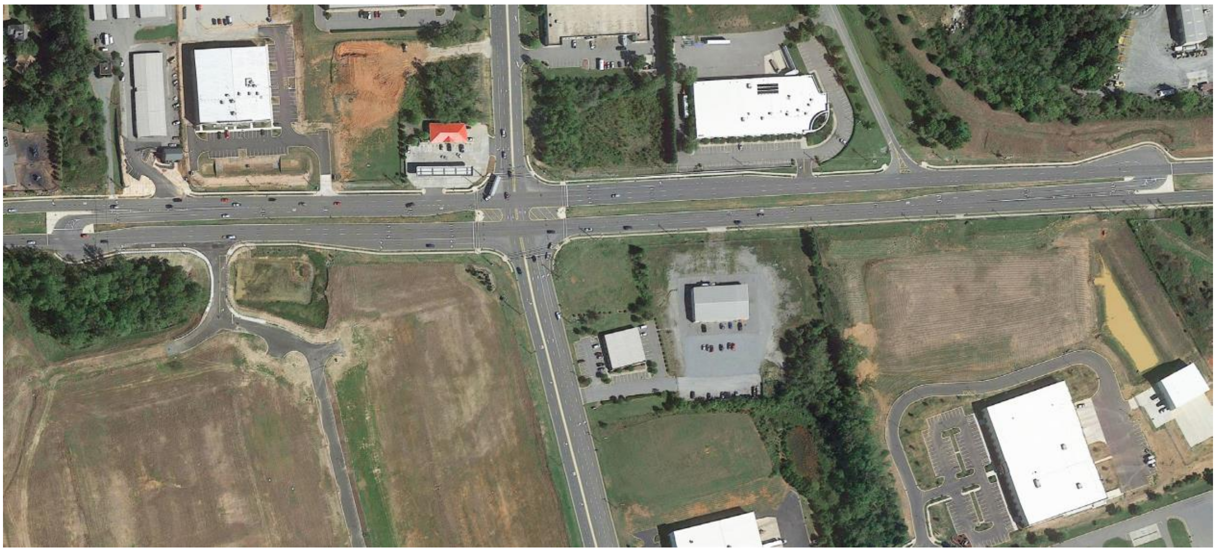


Figure 66 Poplar Tent Road at Derita Road, Concord, N.C.

The Median U-Turn (MUT) is made up of one main intersection and two median crossover intersections. All left-turns are completed by making a U-turn by one of the median crossovers. Traffic that wishes to go straight ahead or turn right proceed as they would on conventional intersections. It is also possible to use roundabouts instead of U-turns. In that case the intersection is called a Bowtie. The MUT can be designed as signalized, stop controlled, or yield controlled. This design can be considered in urban and suburban areas and is suitable under conditions with moderate to heavy through-traffic volumes on the main road and low to moderate left-turn traffic volumes from all approaches. The MUT has 16 conflict points, consisting of 4 crossing, 6 merging, and 6 diverging conflict points. On the other hand, a conventional intersection has 32 conflict points, consisting of 16 crossing, 8 merging, and 8 diverging conflict points. The vehicular movements on this type of intersection are illustrated below.

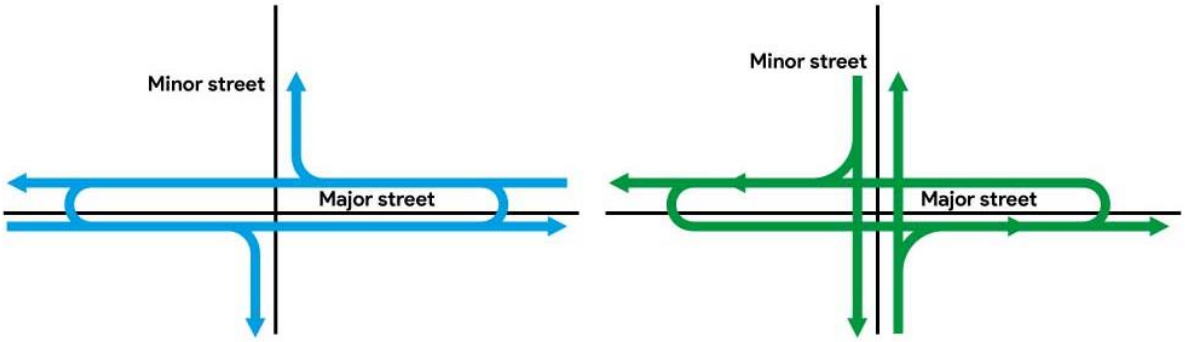


Figure 67 Vehicular movements on a Median U-Turn. Left: major street movements. Right: minor street movements

Advantages (Wilbur Smith Associates et al., 2008)

- By prohibiting left-turns at the main intersection, the initial signal with four phases is reduced to only two.
- With only two phases, the road capacity increases.
- Dependent on the development in its vicinity, the constructional costs are relatively low.
- Overall reduction in crashes (Federal Highway Administration, McLean, VA. 34, 2007)
- The number of crossing conflict points reduces by half, indicating a positive impact on traffic safety.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- Compared to a conventional intersection, it can become less efficient if there are heavy volumes of left-turn and through going traffic from the side streets.
- New intersection with U-turns is something new. Drivers have to get used to the unconventional intersection.
- It is possible that too much weaving is involved between the main intersection and a U-Turn.

Quadrant Roadway


Figure 68 State Route 4 at State Route 4 Bypass/Ross Road, Fairfield, Ohio.

The Quadrant Roadway (QR) is a type of intersection consisting of one main intersection and two secondary intersections that are connected with a connector road in any quadrant of the intersection. Vehicles wanting to make a left-turn at the main intersection are rerouted with the connector road, to complete the left-turn movements. In which quadrant the connector road should be implemented depends on the left-turn demand. Typically, the direction with the highest left-turn demand uses the most direct route, while the longer route is allocated to the direction with the lowest demand. The secondary intersections are signalized but can also be designed without any signals, thus stop or yield controlled. When all three intersections are signalized, traffic signals are synchronized in a way to create a green wave. This design can be considered in urban and suburban areas when heavy through and left-turning traffic volumes are present in all directions. Below, the left-turn movements from two approaches are shown. The QR has 30 conflict points, consisting of 10 crossing, 10 merging, and 10 diverging conflict points. On the other hand, a conventional intersection has 32 conflict points, consisting of 16 crossing, 8 merging, and 8 diverging conflict points.

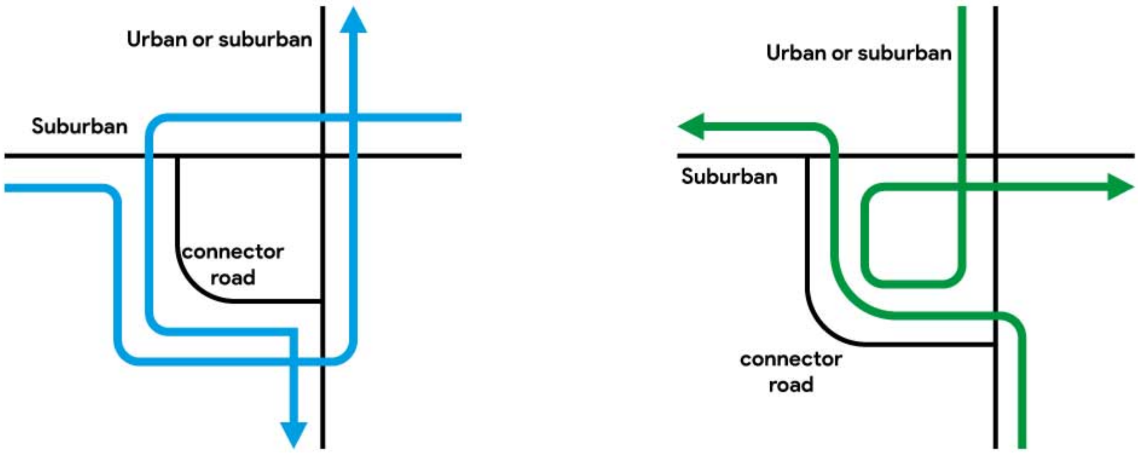


Figure 69 Vehicular movements on a Quadrant Roadway from two different approaches

Advantages

- The intersection can also be implemented as an adjustment to existing infrastructure, where existing streets could function as the connector road. However, it must be taken into account that the road capacity is sufficient. If all of this is the case, a very cost-efficient intersection is created.
- From a geometric perspective, it is relatively easy to design and implement.
- The signalized main intersection requires only two phases when all left turns are prohibited. Simultaneously, this results in three phases on the signalized secondary intersections. In other words, the traffic flow improves.
- The traffic light system can be synchronized in a way to create a green wave. This way the motorized vehicles do not have to stop at every intersection.
- The number of conflict points is spread out from one intersection to three and is slightly reduced.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- If all left-turns are prohibited it means that these will all use the connector road. Therefore, a sufficient road capacity and traffic flow is necessary.

- Prohibiting left-turns may be quite unusual. This is something that road users have to get used to.
- The synchronized traffic light system is relatively complex to design. Besides the green wave for motorized vehicles, the pedestrians and cyclists need a sufficient amount of time to cross the road.
- The number of conflict points might be spread out, but the number of intersections increase.

Restricted Crossing U-Turn

Figure 70 Highway 9 East at Liberty Church Road, Loris, S.C.

The side street movements on the Restricted Crossing U-Turn (RCUT) begin with a right turn. Subsequently, through and left-turning vehicles from the side street make a U-turn at the designated locations, then complete the movement towards the desired direction. The main intersection and U-turns can be designed as signalized, stop controlled or yield controlled. The vehicular movements on this type of intersection are illustrated below. This design can be considered in urban and suburban areas when heavy through and/or left-turning traffic volumes are present on the main road. Further, the side street can only have low through and left-turning traffic volumes. The RCUT has 18 conflict points, consisting of 2 crossing, 8 merging, and 8 diverging conflict points. On the other hand, a conventional intersection has 32 conflict points, consisting of 16 crossing, 8 merging, and 8 diverging conflict points.

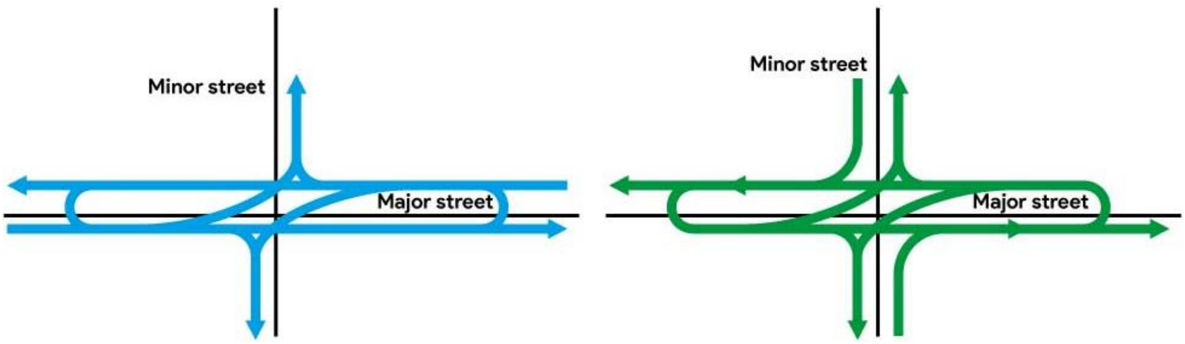


Figure 71 Vehicular movements on a Restricted Crossing U-Turn. Left: major street movements. Right: minor street movements

Advantages

- It has a reduced number of conflict points, improving the traffic safety
- The signalized main intersection requires only two phases.
- It improves the progression of traffic platoons on the suburban road.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- Compared to a conventional intersection, it can become less efficient if there are heavy volumes of left-turn and through going traffic from the side streets.
- This intersection with U-turns is something new. Drivers have to get used to the unconventional intersection.
- It is possible that too much weaving is involved.

A2. Interchanges

Displaced Left-Turn Interchange

Figure 72 I-35 at East Hopkins Street, San Marcos, TX.

Similar to the intersection variant, however now with either an overpass or underpass. With the use of the crossovers, the left-turn vehicles cross the other side of the opposing through traffic before approaching the freeway ramps. The left-turns and opposing through movements occur simultaneously at the two ramp intersections, which reduces the number of signal phases and delay. Further, the intersections and crossovers are signalized and synchronized to minimize stops. This design can be considered in suburban areas when heavy through traffic volumes are present on the side street (i.e., the road with the intersections). Further, traffic onto the ramps may be moderate to heavy traffic volumes. From the ramps to the side street, only low to moderate left-turning traffic volumes may be present. The DLT-interchange consists of 22 conflict points. These are 6 crossing, 8 merging, and 8 diverging conflict points. The number of conflict points (also per conflict type) is the same as for a conventional diamond interchange.

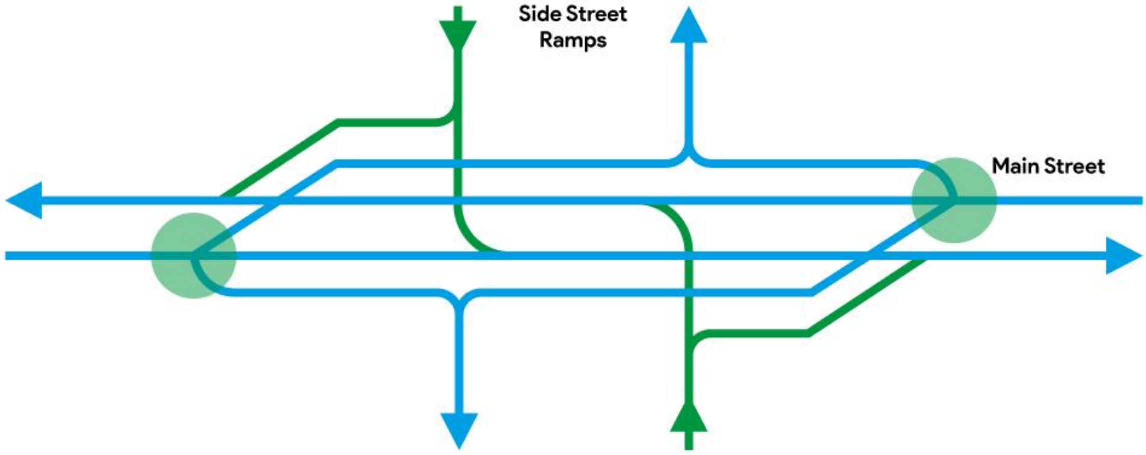


Figure 73 Vehicular movements on a DLT interchange

Above, an illustration of a DLT interchange is shown with colored lines indicating the movements and directions. The green lines indicate the approaching vehicles from the side street ramps, while the blue lines indicate the vehicular movements from the main street. The green circles show the locations where the crossovers are located.

Advantages

- A reduced number of phases for traffic lights, compared to conventional diamond interchanges
- The reduced delay improves the traffic flow for all road users
- It is possible to include pedestrian crossings and cycle lanes into the design of the intersection part.

Disadvantages

- Relatively more expensive, compared to a conventional diamond interchange
- The new type of intersection can cause confusion among road users
- Four signalized intersections are necessary. On the other hand, a conventional diamond interchange only required two signalized intersections.

Diverging Diamond Interchange

Figure 74 I-64 at U.S. 15 (James Madison Hwy), Zion Crossroads, Va.

The Diverging Diamond Interchange (DDI) is a grade-separated interchange where traffic from the suburban road navigates between the freeway ramps. Vehicles that want to make left turns first move to the left side of the road between the ramps. As a result, it allows them to continue driving towards the on-ramps without conflicting with the opposing through traffic.

The right-turns on and off the ramps occur either before or after the crossover intersections, which is clearly depicted in the illustration below. Furthermore, both crossover intersections are signalized, and the intersections can be designed as an overpass or underpass. This design can be considered in suburban areas with heavy left-turning traffic volumes entering/exiting the freeway ramps. The DDI has 18 conflict points, consisting of 2 crossing, 8 merging, and 8 diverging conflict points. Contrarily, a conventional diamond interchange has 22 conflict points, consisting of 6 crossing, 8 merging, and 8 diverging conflict points.

The illustration below shows the vehicular movements on a DDI. The colors green and blue indicate the movements of through traffic on the side street, each from a different approach. Red indicates the on and off ramps.

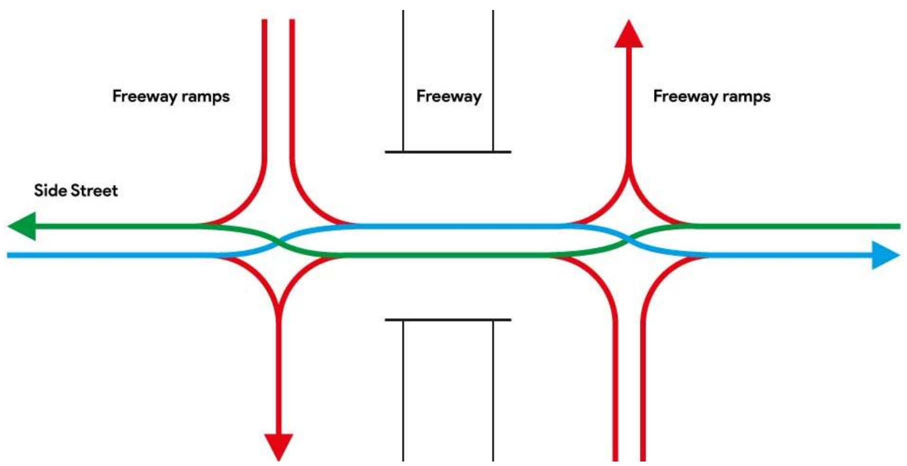


Figure 75 Vehicular movements on a Diverging Diamond Interchange

Advantages

- It improves the traffic flow in cases of high demand of left-turns and through going traffic.
- The signalized intersections require only two phases.
- The design ensures that there are less conflict points, improving the traffic safety compared to a conventional diamond interchange.
- Smaller footprint; Requires less lanes, compared to other interchanges that handle the same amount of traffic.
- Offers constructional cost benefits, compared to other interchanges that handle the same amount of traffic.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- The design is quite unusual as it gives the impression that drivers get to drive on the wrong side of the road. This is something that road users have to get used to.
- Multiple crossings are necessary when pedestrians and cyclists are involved.

Single-Point Urban Interchange

Figure 76 U.S. 50 (Arlington Boulevard) at Gallows Road, Falls Church, Va.

The Single-Point Urban Interchange (SPUI) is a variant of the conventional diamond interchange, where the two intersections have moved to the center, forming a single intersection. All the ramps begin or end at this signalized intersection on the suburban road. The right-turns on and off the ramps occur on bypasses to reduce the load on the main intersection. The intersection platform can be designed as an overpass or underpass. Further, this design can be considered in urban and suburban areas with heavy left-turning traffic volumes entering/exiting the freeway ramps. The SPUI has 24 conflict points, consisting of 8 crossing, 8 merging, and 8 diverging conflict points. On the other hand, a conventional diamond interchange has 22 conflict points, consisting of 6 crossing, 8 merging, and 8 diverging conflict points.

The illustration on the right shows a SPUI interchange with the vehicular movements and directions. Blue is indicating the vehicular movements originating from the freeway ramps, while red indicates the traffic from the side street. Further, yellow indicates the through going traffic on the side streets. Lastly, green indicates all right turns.

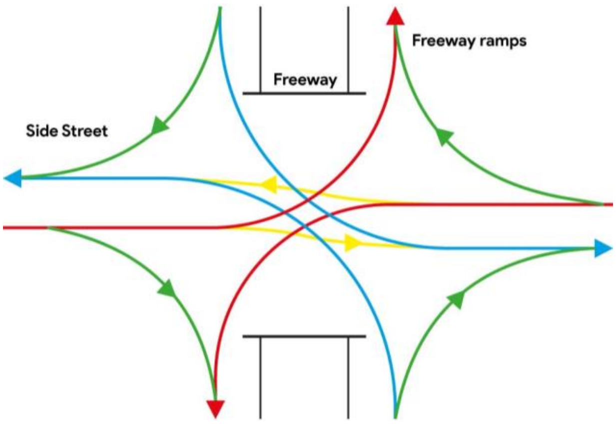


Figure 77 Vehicular movements on a Single-Point Urban Interchange

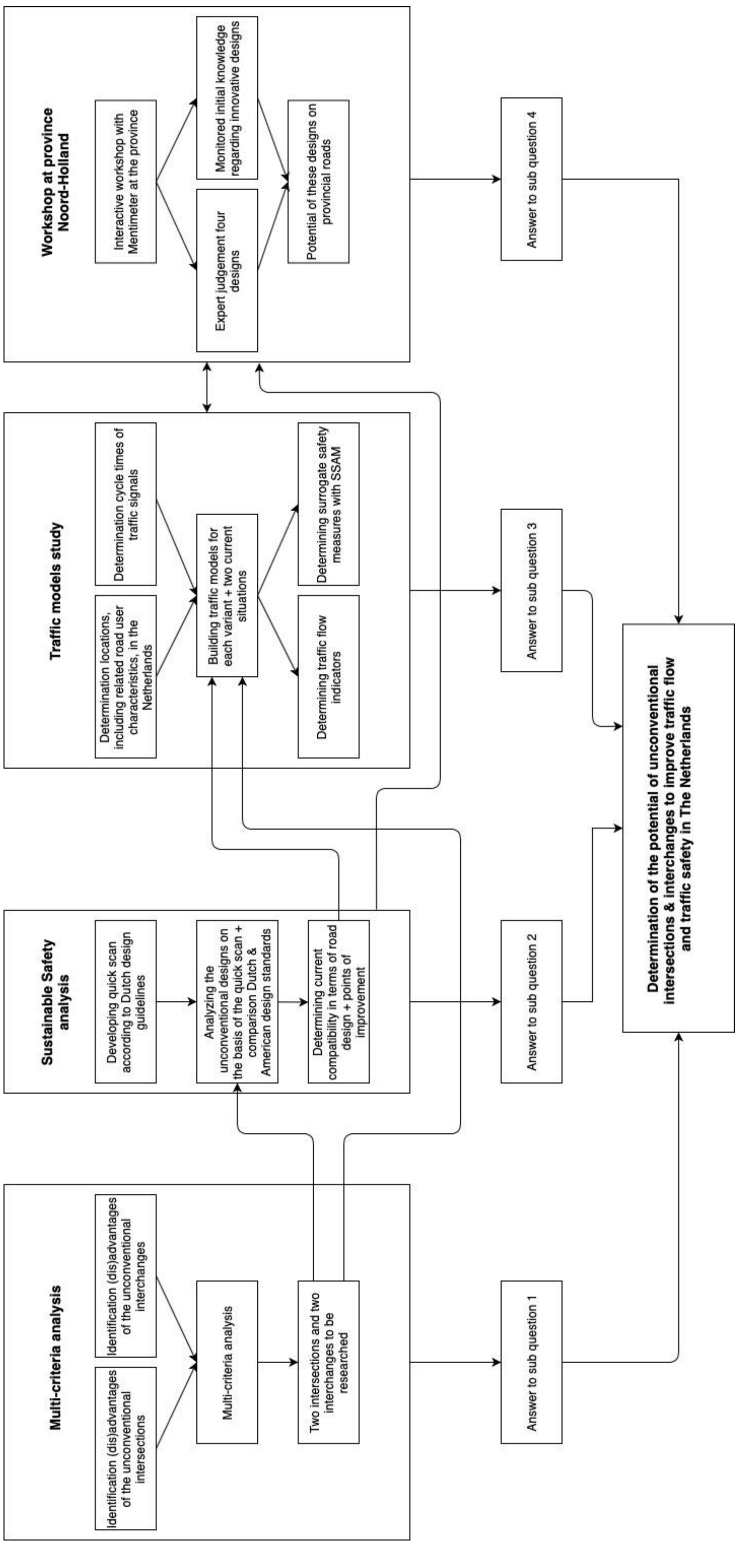
Advantages

- Improved traffic flow and road capacity.
- The signalized main intersection requires three phases.
- Improved traffic safety, as vehicles only have to cross one intersection, instead of two at a conventional diamond interchange.
- It is possible to include pedestrian crossings and cycle lanes into the design.

Disadvantages

- Relatively higher costs compared to a conventional diamond interchange
- Longer clearance times due to the large intersection
- Adding pedestrian crossings and cycle lanes is possible but less convenient compared to a conventional intersection

B
Methodology overview



C
Overview of the reviewed sources

Table 29 Overview of the reviewed sources

Author	Type of design	Country	Purpose	Type of source	Main findings
Virginia Department of Transportation (2021)	General (all chosen designs)	United States	To give an overview of innovative intersections and interchanges.	Governmental webpage	An overview is provided of all the chosen unconventional intersection and interchange designs. The purpose, benefits, conflict points, when it should be considered, and how to navigate is described for each design.
Hughes et al. (2010)	General (all chosen designs)	United States	To provide information regarding various infrastructural characteristics of unconventional designs.	Governmental report	All the chosen unconventional designs are covered in this report. The information in this report provides knowledge of each alternative treatments including salient geometric design features, operational and safety issues, access management issues, costs, and construction sequencing and applicability.
Shumaker et al. (2012)	General	United States	To identify the barriers inhibiting the implementation of promising unconventional designs and to identify solutions.	Scientific paper	Survey results highlight education as important, and that public opinion generally improves once an unconventional design is constructed and experienced. Professionals and politicians want proof that a design will work and are reluctant to try nonstandard designs. An important political consideration is cost, but the life cycle cost can be competitive. It is suggested that guidelines to assist designers are necessary, but also increased focus on alternatives analysis, and inclusion of unconventional designs in planning. This will make the designs more familiar to the public and decrease opposition.
El Esawey & Sayed (2013)	General	United States	To presents an in-depth literature review of existing methods of analyzing the operational and the safety performance of unconventional intersection designs.	Scientific paper	Micro-simulation is used to evaluate the operational performance. Traffic safety evaluation can be done in different ways. These are: 1. Conflict analysis; 2. Before-and-after analysis; 3. Driver confusion/perception analysis; 4. Simulation analysis.
Tarko et al. (2008)	MUT QR RCUT DLT CGT Bowtie	United States	To evaluate the safety and operational impacts of alternative designs.	Governmental report	The presented research developed guidelines for using alternative intersection designs. Knowledge of safety impacts is limited. Further, all intersections are simulated and signalized to test their capacity limits and delay-based performance. Although the roundabouts were the lowest delays at low volumes, they also reached the capacity before other did. The most promising solutions for heavy volumes are MUT and DLT.
Bruce & Gunner (2008)	DLT	United States	To evaluate the advantages and disadvantages of the DLT.	Paper	DLTs are economical, environmentally friendly, safe, faster to construct than grade-separated interchanges, save motorists time, and are well accepted by motorists. Study results using simulation software indicate that DLTs can significantly reduce overall average delay and accidents at some intersections.
Wilbur Smith Associates et al. (2008)	MUT DLT QR CTO	United States	To give an overview of innovative intersections and interchanges.	Governmental report	Broadly outlines information (including advantages and disadvantages) about a variety of innovative intersection concepts and provides more specific implementation

	Echelon CGT DDI Bowtie				guidelines for intersection types that appear to be most applicable to southwest Idaho.
Federal Highway Administration (2020)	DDI	United States	To give an overview of the DDI.	Governmental report	Compared to a conventional diamond interchange, the DDI is a timely, cost-effective solution, integrating all road users. Also, it improves safety while increasing throughput.
Zawawa & Naghawi (2019)	CGT	United States	To evaluate the operational performance of the CGT.	Scientific paper	The simulation results show that the CGT operates the best under stable traffic conditions and that it is not an effective solution for signalized T-intersections under heavy traffic volume.
Cheong et al. (2008)	DLT	United States	To evaluate and compare the operational performance of three unconventional intersections. One of them is the DLT.	Scientific paper	The DLT outperforms the conventional design in terms of traffic flow and reduces delay. Accessibility and land use are problems of the DLT. This in turn affects the costs as well.
Bared, Edara, et al. (2005)	DDI	United States	To evaluate the design and operational performance of the DDI.	Scientific paper	The DDI is studied for different traffic scenarios with the use of traffic simulation, and the results show better performance during peak hours than that of similar corresponding conventional designs. Better performance includes better level of service, shorter delays, smaller queues, and higher throughput.
Chlewicki (2011)	DDI SPUI	United States	To compare the DDI to other interchange forms.	Scientific paper	It is concluded that it is worthwhile to consider the DDI for any interchange improvement when comparing it with other diamond interchange forms. Through simulation it is shown that, when the same number of lanes are considered, the SPUI outperforms the DDI and conventional diamond interchange. It is also shown that if the same number of lanes are considered, the DDI will cost significantly less.
Gettman et al. (2008)	General	United States	To explain the development of the SSAM software tool for deriving surrogate safety measures for traffic facilities from data output by traffic simulation models.	Governmental report	Simulation analysis with SSAM is a modelling technique that combines the output of traffic models and automated conflict analysis to measure the traffic safety. By comparing one simulated design case with another, this software allows an analyst to make statistical judgments about the relative safety of the two designs.
Federal Highway Administration (2016)	CGT	United States	To evaluate the safety performance of the CGT with conventional signalized T-intersections using treatment and comparison sites from Florida and South Carolina.	Governmental report	The results show crashes were reduced for expected total, fatal and injury, and target (rear-end, angle, and sideswipe) crashes at the CGT compared with the conventional signalized T-intersection. Further, the B/C analysis indicated that the CGT is a cost-effective alternative to the traditional, signalized T-intersection. Based on a crash modification factor (CMF), they compared both designs that are located on various locations in Florida and South Carolina. A CMF equal to 1.0 implies that the treatment is not expected to change the number of crashes, while a CMF below 1 implies that the treatment is expected to reduce crashes. The results show that the CMFs associated with total, fatal and injury, and target crashes were 0.886 (11% improvement), 0.884 (12% improvement), and 0.808 (19% improvement), respectively.
Inman (2009)	DLT	United States	To evaluate the DLT's road signs and	Scientific paper	Three different signing strategies were evaluated using a driving simulator. The results show, regardless of which signing

			markings, related driver to confusion.		strategy is used, none of the drivers were confused when they were confronted with the DLT for the first time. The author also suggests that the DLT has the potential to improve the traffic safety while maintaining a high capacity.
Abdelrahman et al. (2020)	DLT	United States	To evaluate the operational and safety performance of the DLT.	Scientific paper	The study concludes that DLTs have negative safety impacts in comparison to conventional intersections for many crash types, but it might be more efficient for operational performance. The safety benefits were determined by estimating the CMF of the DLT. A CMF equal to 1.0 implies that the treatment is not expected to change the number of crashes, while a CMF below 1 implies that the treatment is expected to reduce crashes. According to their analysis, the CMF values were greater than 1.
Park & Rakha (2010)	DLT	United States	To evaluate the safety performance and environmental impact of the DLT.	Scientific paper	The study concludes that drivers are initially unfamiliar with the operational characteristics of DLTs. These problems are found to be temporary and are resolved once drivers become acquainted with the operation of DLTs. Further, the simulation analysis demonstrates how the introduction of a DLT results in operational improvements, fuel savings, and vehicle emissions reductions at different total traffic demand levels and for varying left turn volumes.
Federal Highway Administration (2017)	RCUT	United States	To evaluate the safety performance of a signalized RCUT.	Governmental report	Based on a crash modification factor (CMF), they compared the before and after situation of the signalized RCUT. A CMF equal to 1.0 implies that the treatment is not expected to change the number of crashes, while a CMF below 1 implies that the treatment is expected to reduce crashes. The results of their evaluation show a value of 0.85 for overall crashes (15% improvement), and 0.78 for injury crashes (22% improvement).
Jagannathan (2007)	MUT	United States	To evaluate the safety benefits of the MUT.	Governmental report	The study suggests that the number of collisions could possibly reduce by 20 to 50%, compared to a conventional intersection. The major safety benefit is a reduction in the probability of head-on and angle crashes that typically have high percentages of injury severity.
Kim et al. (2007)	RCUT	United States	To evaluate the safety performance of the RCUT.	Conference	Software tool SSAM is used to make a comparison regarding the traffic safety between an RCUT and a conventional intersection. Two cases were analyzed; however, the results were mixed. In the first case, the RCUT appeared to reduce the number of conflicts by 80% compared to the conventional intersection. In the second case, the results were vice versa, and the number of identified conflicts appeared to be 80% higher for the RCUT.
Zhang & Kronprasert (2013)	RCUT	United States	To evaluate the safety performance of the RCUT.	Conference	The RCUTs in this study are unsignalized. The results show an average reduction of 74%, 57%, and 9% in fatal injury, and property damage only (PDO) crashes.
Claros et al. (2015)	DDI	United States	Safety Evaluation of Diverging Diamond Interchanges in Missouri.	Scientific paper	Study shows that a DDI replacing a conventional diamond interchange decreases the crash frequencies for all severities. In their study, the highest crash reduction was observed for fatal and injury crashes. These were 59.3% and 63.2%, respectively. Also crashes involving property damage were taken into account, which resulted in a reduction of 33.9% to 44.8%. The total crash frequency

					decreased as well, by 40.8% to 47.9%. One issue of the DDI regarding the traffic safety is related to the possibility of wrong-way crashes. The study shows that only 4.8% of all fatal and injury crashes occurring at the ramp terminal of a DDI were wrong-way crashes.
Bared, Powell, et al. (2015)	SPUI	United States	To make a crash comparison between the SPUI and (tight) diamond interchanges.	Scientific paper	Study shows from observed data that the SPUIs were found to be safer than the comparable diamond interchanges for injury/fatality frequencies.
El Esawey & Sayed (2011)	MUT	Egypt	To compare the operational performance of several unconventional intersection designs (among others, the MUT) with the conventional counterparts in Cairo, Egypt.	Scientific paper	The results indicate that the traffic situation improves in terms of level of service. It is shown that the studied alternatives reduce the overall delay and the total travel time, while the average speed increased. The capacity of conventional MUT intersections with signalized and unsignalized crossovers was about 10% and 8% higher than that of the conventional intersection, respectively.
Rahman et al. (2010)	MUT	Bangladesh	To evaluate the operational performance of the MUT, compared to a traditional intersection, through Agent-Based Modelling (ABM).	Conference	The simulation results show that the average travel time to cross the intersection can be reduced by 16.8% when using an MUT intersection. On the other hand, the average number of stops does increase by 5.5% compared to a traditional intersection. Through additional simulation experiments it is concluded that the performance of the MUT is comparatively better in case of moderate to high traffic volumes than low traffic volumes.
Siromaskul (2019)	DDI	France	General design evaluation of the DDI.	Conference	It is being mentioned that the first DDI was built in France.
GWW (2020)	DDI	The Netherlands	To introduce the first American interchange (DDI) in the Netherlands.	Webpage	The article explains that the DDI was experienced positively and has a potential to be used as a permanent solution. On the other hand, the article also mentions that that good communicate and consult well before opening is necessary to avoid many issues. So extensive preparation is necessary.
Arcadis et al. (2020)	DDI	The Netherlands	To evaluate the operational and safety performance of the first DDI in the Netherlands.	Report	The evaluation shows that the DDI functions properly in terms of traffic safety. The reverse driving directions do not cause major problems. There is only an unclear situation when the traffic signals fail, leading to road safety risks. The other findings regarding human factors and traffic safety mainly relate to location-specific characteristics and not so much to the DDI itself. Lastly, it is mentioned that the traffic flow has improved after the realization of the DDI. Due to the positive impact of the DDI on the traffic flow and in general on the traffic safety, it is recommended to use this design more often in the Netherlands.
Pan et al. (2020)	NUUT	China	The introduction and evaluation of the operational performance of a new design: the New Unconventional U-Turn (NUUT) intersection	Scientific paper	This is a modified version of what already exists in the United States, a Median U-Turn intersection, but with the advantage that a distinction is made at the U-turn for small and large vehicles. The purpose of using this paper is to show that new designs are also developed outside of the United States.

D
Motivation scores MCA

Center Turn Overpass (CTO)

Traffic flow impact

As all the left-turns are being elevated, both the intersections require only two phases. On the other hand, a conventional four-legged intersection has at least four phases. With the reduced number of phases, the traffic can flow through the intersection faster, meaning that the traffic flow improves. Furthermore, the design increases the capacity as well. For this reason, 5 points were given regarding the traffic flow impact.

Traffic safety impact

As this design has never been built before, no actual data is available regarding its performance in terms of traffic safety. However, since the number of conflicts is being reduced due to the elevation of the left-turns, it does indicate that it has benefits in terms of traffic safety. Further, the pedestrians and cyclists cross the at-grade intersection the same way as on a conventional intersection. Thus, existing literature shows that there are some traffic safety benefits, but these do not seem to be huge improvements compared to its conventional counterpart. For this design 4 points were allocated.

Technical feasibility

As this design has never been built before, it requires an extensive research before this design can be considered to be added to the Dutch design guidelines. Having two intersections on top of each other would be new in the Netherlands. Moreover, this design only has benefits in road network that have a grid structure. This uncommon in the Netherlands. Hence, the worse score was given regarding the technical feasibility; 1 point.

Ease of use

The design is straightforward. All left-turns make use of the ramps, while the other traffic uses the at-grade intersection. Further, the pedestrians and cyclists cross the at-grade intersection the same way as on a conventional intersection. Therefore, 5 points were allocated.

Use of space

As two intersections are built on top of each other, a lot of space is saved while the capacity is being increased. The ramps have retaining walls, so no additional space is required. Regarding the use of space, 5 points were given.

Costs

The constructional costs are very large in this situation as a grade-separated intersection has to be built. Additionally, due to the patented design, the costs increase even more. Hence, the worse score was given regarding the constructional costs; 1 point.

Continuous Green-T (CGT)

Traffic flow impact

As the CGT has a separate road for through traffic who can pass without any interference, which improves their traffic flow. As a result of separating this road, more green time can be given to the other direction. This reduces the delay. In a study by Zawawa and Naghawi (2019), the operational performance was evaluated of the CGT, compared to a conventional signalized T intersection, under various levels of congestion. The simulation results in their study shows that the CGT operates the best under stable traffic conditions and that it is not an effective solution for signalized T-intersections under heavy traffic volumes. Therefore, 4 points were allocated.

Traffic safety impact

The number of conflicts remain the same, compared to its conventional counterpart. Furthermore, the vehicles that want to make a left-turn from the side street use a bypass to merge onto the major street. Potential angle crashes from the side street are being reduced this way. The Federal Highway Administration (2016) conducted an evaluation of the safety performance of CGTs relative to a conventional signalized T intersection. Based on a crash modification factor (CMF), they compared both designs that are located on various locations in Florida and South Carolina. A CMF equal to 1.0 implies that the treatment is not expected to change the number of crashes, while a CMF below 1 implies that the treatment is expected to reduce crashes. The results show that the CMFs associated with total, fatal and injury, and target crashes were 0.886 (11% improvement), 0.884 (12% improvement), and 0.808 (19% improvement), respectively.

The study does not indicate whether slow traffic is present at these intersections. A disadvantage of the CGT is that pedestrians and cyclists crossing the main road are unprotected by signals. If slow traffic has the opportunity to cross the road, it should be signalized to serve as a form of protection. For this reason, 3 points were allocated.

Technical feasibility

The CGT would be a new design in the Netherlands. The way the design works needs to be incorporated in the Dutch design guidelines before road designers can use this design. Further, the CGT has an extra separated road for through traffic, so reconstruction is necessary when comparing it to a conventional three-legged intersection. All in all, regarding technical feasibility, the CGT is considered to score worse than its conventional counterpart. Therefore, 2 points were allocated.

Ease of use

As this is a new design, it can cause confusion among drivers. Drivers may ignore the separation between the through lanes. This may cause dangerous situations. In terms of ease of use, it is especially beneficial for the through going traffic on the major road. Pedestrians and cyclists can only cross the side street. Therefore, regarding the ease of use, this design scores 2 points. This means that it is worse than a conventional three-legged intersection.

Use of space
Compared to a conventional three-legged intersection, this design requires a separate road for through traffic. Therefore, extra space is necessary. For this reason, only 2 points were allocated regarding the use of space of this design.

Costs
Compared to a conventional three-legged intersection, this design requires a separate road for through traffic. For this reason, only 2 points were allocated regarding the constructional costs of this design.

Displaced Left-Turn (DLT) intersection

Traffic flow impact
By building a DLT intersection, the capacity is being increased, which allows for more traffic at the intersection. The left-turn vehicles use the crossovers to cross to the other side of the road of the opposing through-traffic before arriving at the main intersection. This allows left-turns and opposing through movements to move simultaneously through the main intersection, which reduces the number of signal phases and delay. For this reason, 5 points were given regarding the traffic flow impact.

Traffic safety impact
Compared to a conventional intersection, there is a reduced number of conflict points. This indicates an improvement of traffic safety. On the other hand, the DLT has internal conflict points at the left-turn crossover points. Abdelrahman et al. (2020) conducted safety analyses on the DLT. The results indicate that DLTs can increase crash frequency in comparison to conventional designs. The most significant increasing crash type is single-vehicle which increased by 52%. It is suggested that the increase of this type of crash may be due to drivers' confusion with the non-traditional left-turn maneuver. The safety performance is also estimated by determining the Crash Modification Factor (CMF) of the DLT. The results of the second analysis show as well that the DLT has negative safety impacts. The CMF indicates that for all crash types (except non-motorized crashes), the DLT performs worse than a conventional intersection. Therefore, there are no expected safety benefits associated with the unconventional design. All in all, 2 points were given.

Technical feasibility
The crossovers of the DLT are unknown in the Netherlands. These need to be incorporated in the Dutch design guidelines before road designers can use this design. The design can be considered a bit complex due to the crossovers, which requires some reconstruction to an existing conventional intersection in order to convert it to a DLT. Therefore, 3 points were allocated for this design.

Ease of use
As mentioned before, the crossovers of this design are unknown in the Netherlands. They are not complex but do require road users to get familiar with. Further, this design is less convenient for slow traffic. Pedestrians and cyclists cannot cross all four legs of the intersection. Other than that, traffic that do not turn left will use the main intersection the same way as a conventional one. Additionally, study by Park and Rakha (2010) conclude that drivers are initially unfamiliar with the operational characteristics of DLTs. These problems

are found to be temporary and are resolved once drivers become acquainted with the operation of DLTs. All in all, 3 points were given.

Use of space
The DLT has a larger footprint compared to a conventional intersection. For this reason, only 2 points were allocated regarding the use of space of this design.

Costs
The DLT requires a lot of lanes and therefore, needs more space compared to a conventional intersection. However, it must be noted that this design is only being used as an alternative at locations where it is considered to convert an intersection into an interchange due to traffic congestion. So, with a DLT the capacity is increased, costs are kept low compared to constructing a grade-separated interchange. For this reason, a score of 4 points were allocated.

Echelon

Traffic flow impact
There is a higher road capacity compared to regular at-grade intersections, which also improves the travel time. Further, the signalized intersections require only two phases. All in all, 5 points were given regarding the traffic flow impact.

Traffic safety impact
The number of conflict points are being reduced. This indicates an improvement of traffic safety. On the other hand, a major disadvantage of this design is that pedestrians and cyclists crossing the main road are unprotected by signals. Only 2 points were allocated for this reason.

Technical feasibility
As this design has never been built before, it requires an extensive research before this design can be considered to be added to the Dutch design guidelines. Having two intersections on top of each other would be new in the Netherlands. Moreover, this design only has benefits in road network that have a grid structure. This uncommon in the Netherlands. Hence, the worse score was given regarding the technical feasibility; 1 point.

Ease of use
One approach on both roads is elevated. So, the design is straightforward for motorized vehicles. It is possible to include pedestrian crossings and cycle lanes into the design. However, a staircase or ramp may be required in some locations due to retaining walls or other objects. For this reason, 4 points were allocated.

Use of space
As two intersections are built on top of each other, a lot of space is saved while the capacity is being increased. The ramps have retaining walls, so no additional space is required. Regarding the use of space, 5 points were given.

Costs
Compared to a conventional intersection, the constructional costs are very large in this situation as a grade-separated intersection has to be built. Hence, the worse score was given regarding the constructional costs; 1 point.

Median U-Turn (MUT)

Traffic flow impact
As left-turns are being rerouted, the traffic signals at the main intersection do not need to consider the left-turns anymore. This in turn reduces the number of phases and therefore traffic can be handled through the main intersection faster.

Further, study by Rahman et al. (2019) show through Agent-Based Modeling (ABM) a comparison of the operational performance of the MUT and a conventional four-legged intersection. It must be noted that this study is based on traffic in Bangladesh. The simulation results show that the average travel time to cross the intersection can be reduced by 16.8% when using an MUT intersection. On the other hand, the average number of stops does increase by 5.5% compared to a traditional intersection. Through additional simulation experiments it is concluded that the performance of the MUT is comparatively better in case of moderate to high traffic volumes than low traffic volumes. Additionally, Wilbur Smith Associates et al. (2008) claim that compared to a conventional intersection, the MUT can become less efficient if there are heavy volumes of left-turn and through going traffic from the side streets. This means that the MUT does not perform better under all circumstances. Hence, 4 points were given regarding the impact of the MUT on the traffic flow.

Traffic safety impact
As left-turns are being rerouted, the number of conflict points at the MUT reduces by half, compared to a conventional intersection. This indicates an improvement of traffic safety. The safety evaluation analysis conducted by Jagannathan (2007), determined the traffic safety on a Median U-Turn intersection. Based on his study, he suggests that the number of collisions could possibly reduce by 20 to 50%, compared to a conventional intersection. The main safety benefit is a decrease in the likelihood of head-on and angle crashes that have high injury severity percentages. Regarding the traffic safety impact, 5 points were given.

Technical feasibility
The MUT requires U-Turn, which are unknown infrastructural components in the Netherlands. The U-Turns need to be incorporated in the Dutch design guidelines before road designers can use this design. Further, the MUT does not require a large reconstruction of current situation where a conventional intersection is located. All in all, regarding technical feasibility, the MUT is considered to score slightly worse than a conventional intersection. Therefore, 4 points were allocated.

Ease of use
As U-Turns are new, these require road users to get used to. Pedestrians and cyclists do not face any peculiarities as they cross the intersection the same way as at a conventional type. Study by Jagannathan (2007) suggests that positive guidance communicated through additional signs and road markings may have positive effects to reduce driver confusion and

improving traffic safety. Nonetheless, 4 points were given regarding the ease of use of the MUT.

Use of space
The MUT does not use too much space compared to a conventional intersection. All that is needed is an extra (exit) lane, specifically for traffic wanting to make a U-Turn. And some space for the U-Turn itself, where the turning radii of trucks need to be taken into account. All in all, 4 points was considered to be sufficient regarding the use of space.

Costs
As explained for the use of space, the MUT does not require a large reconstruction. Dependent on the development in its vicinity, the constructional costs are relatively low. For this reason, 4 points were given.

Quadrant Roadway (QR)

Traffic flow impact
If all left-turns are prohibited it means that these will all use the connector road. Therefore, a sufficient road capacity and traffic flow is necessary. Study by Hughes et el., (2010) mentions that the QR offers benefits regarding the operational performance as well. The results conducted from simulations show that the QR performs comparably to a conventional intersection for moderate and balanced through volumes on the major road. On the other hand, the QR shows to have a higher throughput and lower travel times in scenarios where heavy through and moderate left-turn volumes are present on the major road and heavy through and left-turn volumes on the minor road. In these scenarios, the throughput increased 5 to 20%, while the travel times savings were 50 to 200%. All in all, 4 points were allocated.

Traffic safety impact
Despite the fact that this design requires more intersections, the number of conflict points decreases. This is due to the fact that left-turns are being rerouted. This indicates an improvement of traffic safety. Further, prohibiting left-turns may be quite unusual. This is something that road users have to get used to. Moreover, pedestrians and cyclists cross the intersections the same way as on conventional intersections. Thus, slow traffic does not face any possible confusion caused the design. On the other hand, existing literature does not address the experience with existing QRs. Therefore, a good assessment of the traffic safety cannot be made. From the information that is known, 4 points were considered regarding the traffic safety of the QR.

Technical feasibility
The QR consists of infrastructural components that already exist in the Netherlands. Only the functionality of the design is something new as rerouting left-turns are uncommon. Therefore, the QR needs to be incorporated in the Dutch design guidelines before road designers can use this design. All in all, regarding technical feasibility, the QR is considered to score slightly worse than a conventional intersection. Therefore, 4 points were allocated.

Ease of use
As rerouting left-turns is something new, it requires road users to get used to. Pedestrians and cyclists do not experience any peculiarities as they cross the intersections the same way as at a conventional type. Additionally, to reduce driver confusion, positive guidance communicated through additional signs and road markings may be beneficial in this case. Further, the synchronized traffic light system is relatively complex to design. Besides the green wave for motorized vehicles, the pedestrians and cyclists need a sufficient amount of time to cross the road. All in all, 3 points were given.

Use of space
The QR consists of one main intersection, two secondary intersections, and a connector road. This design can be considered to be implemented as an adjustment to existing infrastructure, where existing streets could function as the connector road. If there is a sufficient road capacity, then in this case no physical reconstruction would be necessary. Therefore, 5 points were given.

Costs
As explained for the use of space, when the QR is implemented as an adjustment to existing infrastructure and sufficient road capacity is present, then all that has to be done is reroute left-turns. This is done by adjust the road markings, road signs, and the traffic signals. In other words, as no physical reconstruction is necessary, the costs remain low. For this reason, 5 points were given.

Restricted Crossing U-Turn (RCUT)

Traffic flow impact
In case traffic signals are used to coordinate the traffic on an RCUT, it only requires two phases, while a conventional four-legged intersection has at least four phases. With the reduced number of phases, the traffic can flow through the intersection faster, meaning that the traffic flow improves. However, it must be noted that it can become less efficient if there are heavy volumes of left-turn and through going traffic from the side streets. For this reason, 4 points were given regarding its impact on the traffic flow.

Traffic safety impact
Table 30 (Zhang & Kronprasert, 2013) shows the average before/after annual crashes of RCUTs which are located in Maryland and North Carolina. Before the RCUTs were built, the intersections were uncontrolled priority intersections, where the main road always has priority over the side streets. The RCUTs in this study are also unsignalized. The results show an average reduction of 74%, 57%, and 9% in fatal injury, and property damage only (PDO) crashes. The Federal Highway Administration (2017) did a similar study, but where both situations were signalized. Based on a crash modification factor (CMF), they compared the before and after situation. A CMF equal to 1.0 implies that the treatment is not expected to change the number of crashes, while a CMF below 1 implies that the treatment is expected to reduce crashes. The results of their evaluation show a value of 0.85 for overall crashes (15% improvement), and 0.78 for injury crashes (22% improvement).

Table 30 Average before/after annual crashes of RCUTs in Maryland and North Carolina (Zhang & Kronprasert, 2013)

Location	Fatal Crashes		Injury Crashes		PDO Crashes	
	Before	After	Before	After	Before	After
Maryland						
US 15 & Old Frederick Rd	0.3	0.3	7.0	5.3	7.7	7.7
US 15 & College Ln	0.0	0.0	9.3	1.7	7.0	2.0
US 15 & Sundays Ln	0.0	0.0	4.0	3.0	4.3	5.7
US 15 & Biggs Ford Rd	0.3	0.3	15.3	3.3	12.7	7.0
US 15 & Willow Rd	0.3	0.0	7.3	7.3	9.7	9.0
US 15 & Hayward Rd	0.3	0.0	13.7	19.7	10.7	12.0
US 301 & Galena Rd	0.0	0.3	7.0	0.3	–	–
US 301 & Main St	0.3	0.0	0.7	1.0	–	–
US 301 & Del Rhodes Ave	0.3	0.0	30.3	0.0	–	–
US 301 & Sudlersville Rd	0.0	0.0	3.3	0.7	–	–
US 301 & McGinnes Rd	0.0	0.0	1.0	0.0	–	–
US 301 & Ruthsburg Rd	0.3	0.0	2.7	0.0	–	–
Average	0.19	0.08	8.47	3.52	8.67	7.22
North Carolina						
US17 & Mt. Pisgah/Sellers Rd	0.2	0.0	6.7	1.2	7.9	12.0
US17 & Ocean Isle Beach Rd	0.4	0.0	5.5	0.0	9.6	8.7
US74 & Red Bank/Old Balsam Rd	0.3	0.3	7.0	3.2	3.6	5.1
US74/441 & Barkers Creek Rd	0.0	0.0	3.3	0.0	2.5	4.5
US74/441 & Dicks Creek Rd	0.0	0.0	1.9	3.0	2.5	1.5
US74 & Elmore Rd/SR1321	0.2	0.0	1.7	2.8	1.9	0.0
US74/76 & Blacksmith Rd	0.2	0.0	1.8	1.5	0.8	0.4
NC24 & Haw Branch/SR1230	0.2	0.0	2.3	1.1	5.0	2.3
US1 & Camp Easter/Aiken Rd	0.2	0.0	1.6	2.0	3.6	2.3
NC87 & Peanut Plant Rd/ SR1150	0.2	0.0	6.2	0.3	1.4	3.0
NC87/24 & 2nd Street	0.0	0.0	3.9	2.8	8.3	5.6
NC87 & School/Butler Nursery Rd	0.0	0.0	4.2	2.8	2.6	6.5
NC87 & Grays Creek Church Rd	0.4	0.0	1.8	0.9	3.0	0.0
Average	0.18	0.02	3.67	1.67	4.05	4.00
Overall Average	0.19	0.05	5.98	2.56	5.51	5.01
Average Reduction	74%		57%		9%	

The RCUT ensures that the number of crossing conflict points is drastically reduced, compared to a conventional intersection. This shows that the RCUT has benefits in terms of traffic safety. The only disadvantage regarding the traffic safety that has been found is that the design may confuse drivers. However, the experiences with the RCUT in North Carolina and Maryland show that drivers adapt well to these intersections (Hughes et al., 2010). For this reason, it was chosen to give 5 points to the RCUT regarding its impact on traffic safety.

Technical feasibility
The RCUT requires U-Turn, which are unknown infrastructural components in the Netherlands. The U-Turns need to be incorporated in the Dutch design guidelines before road designers can use this design. Further, the RCUT does not require a large reconstruction of current situation where a conventional intersection is located. All in all, regarding technical feasibility, the RCUT is considered to score slightly worse than a conventional intersection. Therefore, 4 points were allocated.

Ease of use
As U-Turns are new, these require road users to get used to. The crossovers at the main intersection also influence the way slow traffic cross the road. However, as mentioned

before, a study did show that drivers adapt well to the intersection (Hughes et al., 2010). Nonetheless, 3 points were given regarding the ease of use of the RCUT.

Use of space
The RCUT does not show significant differences in the usage of space, compared to a conventional intersection. It is similar to the MUT, where space is mainly needed for the U-turns. For this reason, 4 points were allocated.

Costs
The constructional costs are comparable an MUT. This is due to the fact that both intersection designs use about the same amount of space. 4 points were given regarding the constructional costs of the RCUT.

Displaced Left-Turn (DLT) interchange

Traffic flow impact
By building a DLT interchange, the capacity is being increased, which allows for more traffic at the intersection part of the design. Moreover, the motorway that goes over the intersection allows the traffic to have a free flow. The left-turn vehicles use the crossovers to cross to the other side of the road of the opposing through-traffic before arriving at the main intersection. This allows left-turns and opposing through movements to move simultaneously through the main intersection, which reduces the number of signal phases and delay. For this reason, 5 points were regarding the traffic flow impact.

Traffic safety impact
This design has the same number of conflict points as a conventional diamond interchange. Furthermore, the DLT has internal conflict points at the left-turn crossover points. Abdelrahman et al. (2020) conducted safety analyses on the DLT. The results indicate that DLTs can increase crash frequency in comparison to conventional designs. The most significant increasing crash type is single-vehicle which increased by 52%. It is suggested that the increase of this type of crash may be due to drivers' confusion with the non-traditional left-turn maneuver. The safety performance is also estimated by determining the Crash Modification Factor (CMF) of the DLT. The results of the second analysis show as well that the DLT has negative safety impacts. The CMF indicates that for all crash types (except non-motorized crashes), the DLT performs worse than a conventional intersection. Therefore, there are no expected safety benefits associated with the unconventional design. All in all, 2 points were.

Technical feasibility
The crossovers of the DLT are unknown in the Netherlands. These need to be incorporated in the Dutch design guidelines before road designers can use this design. The design can be considered a bit complex due to the crossovers, which requires some reconstruction to an existing conventional design in order to convert it to a DLT interchange. Therefore, 3 points were for this design.

Ease of use
As mentioned before, the crossovers of this design are unknown in the Netherlands. They are not complex but do require road users to get familiar with. Further, this design is less

convenient for slow traffic. Pedestrians and cyclists cannot cross all four legs of the intersection part of the design. Other than that, traffic that do not turn left will use the main intersection the same way as a conventional one. Additionally, study by Park and Rakha (2010) conclude that drivers are initially unfamiliar with the operational characteristics of DLTs. These problems are found to be temporary and are resolved once drivers become acquainted with the operation of DLTs. All in all, 3 points were given.

Use of space
The DLT has a significantly larger footprint compared to a conventional diamond interchange. For this reason, only 1 point was allocated regarding the use of space of this design.

Costs
The DLT interchange requires a lot of lanes and therefore, needs more space compared to a conventional design. Moreover, when taking into account that the design includes a flyover, the costs will be significantly higher than a conventional diamond interchange. Hence, only 1 point were allocated.

Diverging Diamond Interchange (DDI)

Traffic flow impact
Vehicles that want to make left-turns first move to the left side of the road between the ramps. As a result, it allows them to continue driving towards the on-ramps without conflicting with the opposing through traffic. Further, in research from Bared, Edara, et al. (2005) the operational performance of the DDI is being compared to a conventional diamond interchange. The study concludes through simulations that for higher traffic volumes, the DDI has better performance in terms of traffic flow and offers lower delays, lesser number of stops, lower stop time and shorter queue lengths as compared to the operational performance of its conventional counterpart. However, for medium and lower volumes, the performance of a DDI is identical to a conventional diamond interchange. As the DDI does not outperform the conventional design all levels of congestion, 4 points werebeen allocated regarding the traffic flow impact.

Traffic safety impact
The design ensures that there are less conflict points, improving the traffic safety compared to a conventional diamond interchange. Furthermore, study by Claros et al. (2015) shows that a DDI replacing a conventional diamond interchange decreases the crash frequencies for all severities. In their study, the highest crash reduction was observed for fatal and injury crashes. These were 59.3% and 63.2%, respectively. Also crashes involving property damage has been taken into account, which resulted in a reduction of 33.9% to 44.8%. The total crash frequency decreased as well, by 40.8% to 47.9%. One issue of the DDI regarding the traffic safety is related to the possibility of wrong-way crashes. The study shows that only 4.8% of all fatal and injury crashes occurring at the ramp terminal of a DDI were wrong-way crashes. All in all, the DDI offers significant crash reduction benefits over its conventional counterpart. Therefore, 5 points were allocated.

Technical feasibility
In 2019, the DDI has been built for the first time in the Netherlands as a temporary interchange (GWW, 2020). The article explains that the DDI has been experienced positively and has a potential to be used as a permanent solution. This is confirmed by the evaluation report by Arcadis (2020). Nonetheless, this design needs to be added to the Dutch design guidelines before it can be built nationwide. Whether this is already considered or how long this will take to be added is unknown. For this reason, 4 points were given.

Ease of use
The article by GWW (2020) says that good communicate and consult well before opening is necessary to avoid many issues. So extensive preparation is necessary. Moreover, multiple crossings are necessary when pedestrians and cyclists are involved, which makes it the DDI less convenient for slow traffic. All in all, 3 points were given regarding the ease of use of the DDI.

Use of space
The DDI is a large structure. However, the DDI requires fewer lanes, compared to a conventional diamond interchange to handle the same amount of traffic. In other words, this means that the DDI has a smaller footprint, which causes the DDI to have fewer impacts to adjacent areas (Federal Highway Administration, 2020). Therefore, 4 points were given.

Costs
In terms of construction cost savings, a project that converted an existing interchange into a DDI in Springfield, Missouri, saved 6.8 million dollars compared with a SPUI or widening of the existing conventional diamond interchange (Maji et al., 2013). This means the DDI offers significant cost benefits, compared to other alternatives. Therefore, 5 points were allocated.

Single-Point Urban Interchange (SPUI)

Traffic flow impact
In research from Chlewicki (2012) the SPUI is being compared in terms of its operational performance, to a Diverging Diamond Interchange (DDI), and a conventional diamond interchange. Through simulation it is shown that, when the same number of lanes are considered between all the designs, the SPUI outperforms the rest. Therefore, 5 points were given.

Traffic safety impact
Despite the fact that the SPUI has a slightly increased number of conflict points compared to a conventional diamond interchange, the traffic safety does improve as the SPUI only requires one intersection. Further, study by Bared, Powell, et al., (2005) shows from observed data that the SPUIs were found to be safer than the comparable diamond interchanges for injury/fatality frequencies. Further, no major disadvantages regarding safety can be found in recent literature. Therefore, 4 points were allocated.

Technical feasibility
The intersection platform of the SPUI is unknown in the Netherlands. This needs to be incorporated in the Dutch design guidelines before road designers can use this design. The on and off ramps are similar to a conventional diamond interchange. The design can be

considered a bit complex due to large platform, and requires some reconstruction to an existing conventional design in order to convert it to a SPUI. Therefore, 3 points were allocated for this design.

Ease of use

Compared to the other alternatives, the SPUI only requires one intersection. On the other hand, the way traffic is exchanged on the intersection is different from the conventional intersection. This is something that road users have to get used to. Pedestrians and cyclists cannot cross the arterial. They can only cross the on and off ramps, thus parallel to the arterial. Therefore, this design is less convenient compared to a conventional design. All in all, 4 points were given.

Use of space

No significant differences in the use of space between a SPUI and a conventional diamond interchange can be observed. Hence, 3 points were given.

Costs

The SPUI can be built more compact than a conventional design. However, the SPUI does have a large intersection platform. Study by Chlewicki (2012) shows that if the same number of lanes are considered, the DDI will cost significantly less. Only 2 points were allocated regarding the constructional costs.

0-1 Using a picture, show the intersection/interchange and number each road (section).

Functionality

The following first four questions determine the functionality of the traffic system based on the geometry. The remaining two questions determine the functionality based on traffic signs present at the location. Possible present traffic signs are depicted as well in the question. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

1-1 Which parts of the infrastructure are designed to let traffic flow? (Multiple answers possible)

O One of the intersecting roads: separate lanes per direction, slow traffic and fast traffic are separated.

O Interchanges: exchanging traffic to surrounding areas while maintaining an ongoing traffic flow.

O None of the above.

1-2 Which parts of the infrastructure are designed to exchange traffic? (Multiple answers possible)

O One of the intersecting roads: provides access to nearby destinations.

O Intersections: Exchanging traffic at-grade with the surroundings.

O None of the above.

1-3 Which parts of the nearby roads are designed on a residential function? (Multiple answers possible)

O The residential area is located next to one of the intersecting roads.

O One of the intersecting roads has a mixed residential and traffic function (no separate roadways).

O None of the above.

1-4 Is there a transition of road type on any of the nearby roads?

O Yes.

O No.

1-5 What type of traffic signs are used?

O 

(25 speed limit, stop and yield signs) ➔ Local road
(Erftoegangsweg)

O 

(speed limit 30 and warning pedestrian crossing) ➔ Collector/distributor
(Gebiedsontsluitingsweg binnen de bebouwde kom)

O 

(speed limit 40 and boulevard signs) ➔ Arterial
(Gebiedsontsluitingsweg buiten de bebouwde kom)

O 

(speed limit 80 and interstate route signs) ➔ Freeway
(Stroomweg)

O None of the above

1-6 Are one of the intersection roads (according to the traffic signs) located inside or outside urban areas?
O Inside urban areas.
O Outside urban areas (suburban).

1-7 Regarding mono functionality, the crossing roads are designed as a:
(Multiple answers possible, indicate the roads with numbers on a map)
O Freeway: flow function, serves to let high volumes of traffic flow
O Arterial: exchanges traffic from collector roads to freeways
O Collector/distributor: exchanges traffic from local roads to arterials
O Local road: exchange function, serves to give access to residences
O Gray road: road has a flow and exchange function

1-8 Do the American traffic rules according to the traffic signs correspond to the actual function of the traffic system?
O Yes.
O No.
O N/a (the traffic rules are not unambiguously determined by present traffic signs)

1-9 Do the Dutch traffic rules according to the traffic signs correspond to the actual function of the traffic system?
O Yes.
O No.
O N/a (the traffic rules are not unambiguously determined by present traffic signs)

Additional explanation:

(Bio)mechanics

This principle is in twofold. Firstly, it is related to the homogenization of the traffic system, meaning that limiting the differences in speed, direction, mass and size is desired, and giving road users appropriate protection. Secondly, physical forgiveness of the traffic system is taken into account. This is related to aspects such as whether there is enough space on the road in case maneuvers by road users is required, or to certain objects which may block the road or view. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

Homogenization

2-1 What are the speed limits on the crossing roads?
Major road: …
Side street: …

2-2 What are the types of road users that are present at the location? (Multiple answers possible)
O Pedestrians
O Bicycles/mopeds
O Motorcycles/cars/vans
O Trucks
O Public transport, such as: …

2-3 Regarding the whole traffic system, are there any possibilities for conflicts between slow traffic and motorized traffic?
O Yes.
O Only potential. For example, when red traffic lights are (intentionally/unintentionally) ignored. Potential conflicts could also occur when slow and motorized traffic are not physically separated.
O No, due to physical separation of slow and motorized vehicles, possibilities of conflicts are very unlikely.

2-4 Are there possibilities for transverse conflicts between motorized traffic on the road?
O Yes.
O Potential conflicts are possible, for example, when red traffic lights are (intentionally/unintentionally) ignored.
O No.

2-5 When excluding the intersections/interchanges, are there possibilities for frontal conflicts between motorized traffic within the traffic system?
O Yes, for example when vehicles overtake.
O Only potential. For example, when (intentionally/unintentionally) crossing the center road marking that divides two-way traffic.
O No, due to physical separation, possibilities of frontal conflicts are very unlikely.

2-6 On places with (potential) conflicts between cyclists/pedestrians and motorized traffic, the speed of motorized traffic is limited to approximately 30 km/h:
O Yes (or n/a).

O No, but these conflicts do not occur regularly, and the speed does not exceed about 50 km/h.
O No, these conflicts occur at higher speeds.

2-7 On one of the intersecting road sections and intersections with potential crossing conflicts between motorized vehicles, the speed of motorized traffic is limited to approximately 50 km/h:
O Yes (or n/a).
O No, but these conflicts do not occur regularly, and the speed does not exceed about 70 km/h.
O No, these conflicts occur at higher speeds.

2-8 On one of the intersecting road sections with (potential) frontal conflicts, the speed of motorized traffic is limited to approximately 70 km/h:
O Yes (or n/a).
O No, but these conflicts do not occur regularly, and the speed does not exceed about 80 km/h.
O No, these conflicts occur at higher speeds.

Physical forgiveness
2-9 Regarding physical forgiveness, the physical boundaries of roadways are designed in such a way that a sufficient width has been used for narrow-paved shoulders:
O Yes (or n/a).
O Approximately. There is some space available for narrow-paved shoulders, but it is not as wide as prescribed in the (Dutch or American) design guidelines.
O No, but it is desired to have narrow-paved shoulders.

2-10 Stopping sight: What is the approximate minimum available sight that is needed to be able to come to a stop in time for discontinuities such as intersections, obstacles, or stationary traffic?

2-11 Driveway sight: What is the approximate minimum available sight for traffic to know if they can cross the road without interfering with crossing traffic, when standing 5 meters before the intersection?

Additional explanation:

Psychology

Psychology is related to how well the traffic system is designed in a way that especially older road users are capable of recognizing how to safely participate in traffic. This means that even for them the information from the traffic system should be observable, self-explaining, credible, relevant, and executable. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

3-1 What type of lanes are present on the roads? Indicate the road numbers on a map. (Multiple answers possible)

Road 1	**Road 2**	**Road 3**
O Traffic lane	O Traffic lane	O Traffic lane
O Hard shoulder	O Hard shoulder	O Hard shoulder
O Auxiliary lane	O Auxiliary lane	O Auxiliary lane
O Truckway	O Truckway	O Truckway
O Bus lane	O Bus lane	O Bus lane
O Bicycle lane	O Bicycle lane	O Bicycle lane
O Sidewalk	O Sidewalk	O Sidewalk
O Clear zones	O Clear zones	O Clear zones
O Others:	O Others:	O Others:

Use Table 32 in the Appendix to determine whether the width of each lane type complies with the American and Dutch design guidelines.

3-2 Are these lanes according to the American guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Road 1

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines

3-3 Are these lanes according to the Dutch guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines

3-4 When road markings are obstructed due to snow, to what extent can the intersection/interchange confuse the road user?

O It will not confuse the road users. For example, due to physically separated roads/lanes.

O Potential confusion only among motorized vehicles. Only road signs will help the vehicles navigate through the intersection/interchange.

O Possibilities of severe accidents.

Additional explanation:

Tables used in the desk investigation

Table 31 Elaboration of "safe speed limits". Differences from the row above are highlighted ***in bold****. (SWOV, 2018a)*

Potential conflict situations and conditions associated with it	Safe speed
• Possible conflicts with vulnerable road users on yards (no sidewalks present, and pedestrians use the entire roadway)	15 km/h
• Possible conflicts with vulnerable road users **on roads, intersections, also in situations with bicycle lanes or shoulders**	30 km/h
• **No conflicts with vulnerable road users, with the exception of motorized two-wheelers with helmets (moped on the roadway)** • Possible transverse conflicts between car traffic, possible frontal conflicts between car traffic • **Stopping sight distance ≥ 47 m**	50 km/h
• No conflicts with vulnerable road users • **No transverse conflicts between car traffic**, possible frontal conflicts between car traffic • **Obstacles shielded or obstacle-free zone ≥ 2.5 m, (semi) paved shoulder** • **Stopping sight distance ≥ 64 m**	60 km/h
• No conflicts with vulnerable road users • No transverse conflicts between car traffic, possible frontal conflicts between car traffic • Obstacles protected or **obstacle-free zone ≥ 4.5 m**, (semi) paved shoulder • **Stopping sight distance ≥ 82 m**	70 km/h
• No conflicts with vulnerable road users • **No transverse and frontal conflicts between car traffic** • Obstacles shielded or **obstacle-free zone ≥ 6 m**, (semi) paved shoulder • **Stopping sight distance ≥ 105 m**	80 km/h
• No conflicts with vulnerable road users • No cross and frontal conflicts between car traffic • Obstacles shielded or **obstacle-free zone ≥ 10 m, hard shoulder** • **Stopping sight distance ≥ 170 m**	100 km/h
• No conflicts with vulnerable road users • No cross and frontal conflicts between car traffic • Obstacles shielded or **obstacle-free zone ≥ 13 m**, paved shoulder. **Stopping viewing distance ≥ 260 m**	120 km/h
• No conflicts with vulnerable road users • No cross or frontal conflicts between car traffic • Obstacles shielded or **obstacle-free zone ≥ 14.5 m**, paved shoulder. **Stopping viewing distance ≥ 315 m**	130 km/h

Table 32 Lane types and widths according to American and Dutch design guidelines

Lane types	Width according to American guidelines (m)	Width according to Dutch guidelines (m)
Traffic lane 1. Freeway (stroomweg) 2. Arterial (gebiedsontsluitingsweg buiten de bebouwde kom) 3. Collector/distributor (gebiedsontsluitingsweg binnen de bebouwde kom) 4. Local road (erftoegangsweg)	1. 3.60 2. 3.0 to 3.60 3. 3.0 to 3.30 4. 3.0 to 3.30	1. 3.0 to 3.25 2. 3.0 to 3.10 3. 3.0 to 3.10 4. 3.0, or 4.50 in cases with no road markings.
Hard shoulder	- 3.0 to 3.60 for emergency lanes. - 0.30 to 0.60 (narrow-paved shoulder). - 1.20 If cyclists are to be accommodated on the shoulders. - 1.80 to 2.40 for low-volume highways.	- 3.0 to 3.60 for emergency lanes. - 0.60 on freeways (narrow-paved shoulder). - 0.30 on arterials and collectors/distributors (narrow-paved shoulder). - 1.25 If cyclists are to be accommodated on the shoulders.
Auxiliary lane - Acceleration lane - Deceleration lane	3.0 to 4.80	3.0
Truckway/lanes with high volume of trucks	3.60	3.0
Bus lane	3.30 to 3.60	3.10
Bicycle lane	- 1.20 If cyclists are to be accommodated on the shoulders - 1.50 desired - 1.80 to 2.40 for areas with high bicycle use (AASHTO, 2012)	- 1.50 - 1.25 If cyclists are to be accommodated on the shoulders - 3.50 if two-lane cycle path separated from the road.
Sidewalk (minimum	1.50	1.50
Clear zones (minimum)	Depends on speed and average daily traffic. For full list, see Table 33. - ≤60 km/h: 2.0	- 60 km/h: 3.0 - 80 km/h: 4.50 - ≥100 km/h: 6.0

	- 70-80 km/h: 3.0 - ≥100 km/h: 5.0	

Table 33 Suggested distances in obstacle-free zones in meters from the edge of the through lane. ADT stands for Average Daily Traffic. (AASHTO Roadside Design Guide (2011)

Design Speed (km/h)	Design ADT	Foreslopes			Backslopes		
		1V:6H or flatter	1V:5H to 1V:4H	1V:3H	1V:3H	1V:5H to 1V:4H	1V:6H or flatter
≤60	UNDER 750[c]	2.0–3.0	2.0–3.0	[b]	2.0–3.0	2.0–3.0	2.0–3.0
	750–1500	3.0–3.5	3.5–4.5	[b]	3.0–3.5	3.0–3.5	3.0–3.5
	1500–6000	3.5–4.5	4.5–5.0	[b]	3.5–4.5	3.5–4.5	3.5–4.5
	OVER 6000	4.5–5.0	5.0–5.5	[b]	4.5–5.0	4.5–5.0	4.5–5.0
70–80	UNDER 750[c]	3.0–3.5	3.5–4.5	[b]	2.5–3.0	2.5–3.0	3.0–3.5
	750–1500	4.5–5.0	5.0–6.0	[b]	3.0–3.5	3.5–4.5	4.5–5.0
	1500–6000	5.0–5.5	6.0–8.0	[b]	3.5–4.5	4.5–5.0	5.0–5.5
	OVER 6000	6.0–6.5	7.5–8.5	[b]	4.5–5.0	5.5–6.0	6.0–6.5
90	UNDER 750[c]	3.5–4.5	4.5–5.5	[b]	2.5–3.0	3.0–3.5	3.0–3.5
	750–1500	5.0–5.5	6.0–7.5	[b]	3.0–3.5	4.5–5.0	5.0–5.5
	1500–6000	6.0–6.5	7.5–9.0	[b]	4.5–5.0	5.0–5.5	6.0–6.5
	OVER 6000	6.5–7.5	8.0–10.0[a]	[b]	5.0–5.5	6.0–6.5	6.5–7.5
100	UNDER 750[c]	5.0–5.5	6.0–7.5	[b]	3.0–3.5	3.5–4.5	4.5–5.0
	750–1500	6.0–7.5	8.0–10.0[a]	[b]	3.5–4.5	5.0–5.5	6.0–6.5
	1500–6000	8.0–9.0	10.0–12.0[a]	[b]	4.5–5.5	5.5–6.5	7.5–8.0
	OVER 6000	9.0–10.0[a]	11.0–13.5[a]	[b]	6.0–6.5	7.5–8.0	8.0–8.5
110[d]	UNDER 750[c]	5.5–6.0	6.0–8.0	[b]	3.0–3.5	4.5–5.0	4.5–5.0
	750–1500	7.5–8.0	8.5–11.0[a]	[b]	3.5–5.0	5.5–6.0	6.0–6.5
	1500–6000	8.5–10.0[a]	10.5–13.0[a]	[b]	5.0–6.0	6.5–7.5	8.0–8.5
	OVER 6000	9.0–10.51	11.5–14.0[a]	[b]	6.5–7.5	8.0–9.0	8.5–9.0

Table 34 Driveway sight at 30-60 km/h (CROW, 2013).

Naderingssnelheid hoofdweg (km/h)	Oprijzicht vanaf zijweg (m)
30	75
60	100

Table 35 Driveway sight at 80 km/h (CROW, 2013).

Aard manoeuvre	Kritisch tijdsinterval (s)		Oprijzicht bij 80 km/h (m)	
	wegtype I	wegtype II	wegtype I	wegtype II
Linksaf vanaf hoofdrijbaan	5,5	5,0	125	110
Rechtsaf vanaf zijweg	5,5	5,5	125	125
Rechtdoor vanaf zijweg	6,5	6,0	145	135
Linksaf vanaf zijweg	7,0	6,5	155	145

Desk investigation Sustainable Safety location 1 – Median U-Turn

0-1 Using a picture, show the intersection/interchange and number each road (section).

Location: Poplar Tent Road at Derita Road, Concord, N.C.

Figure 78 Poplar Tent Road at Derita Road, Concord, N.C.

Functionality

The first four questions determine the functionality of the traffic system based on the geometry. The other two questions determine the functionality on the basis of traffic signs present at the location. Traffic signs that may be present are also depicted in the question. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

1-1 Which parts of the infrastructure are designed to let traffic flow? (Multiple answers possible)

O One of the intersecting roads: separate lanes per direction, slow traffic and fast traffic are separated.

O Interchanges: exchanging traffic to surrounding areas while maintaining an ongoing traffic flow.

X None of the above.

1-2 Which parts of the infrastructure are designed to exchange traffic? (Multiple answers possible)

X One of the intersecting roads: provides access to nearby destinations.

X Intersections: Exchanging traffic at-grade with the surroundings.

O None of the above.

1-3 Which parts of the nearby roads are designed on a residential function? (Multiple answers possible)

X The residential area is located next to one of the intersecting roads.

O One of the intersecting roads has a mixed residential and traffic function (no separate roadways).

O None of the above.

1-4 Is there a transition of road type on any of the nearby roads?
O Yes.
☒ No.

1-5 What type of traffic signs are used?

O 

(25 speed limit, stop and yield signs) ➔ Local road
(Erftoegangsweg)

O 

(speed limit 30 and warning pedestrian crossing) ➔ Collector/distributor
(Gebiedsontsluitingsweg binnen de bebouwde kom)

☒ 

(speed limit 40 and boulevard signs) ➔Arterial
(Gebiedsontsluitingsweg buiten de bebouwde kom)

O 

(speed limit 80 and interstate route signs) ➔ Freeway
(Stroomweg)

O None of the above

1-6 Are one of the intersection roads (according to the traffic signs) located inside or outside urban areas?
O Inside urban areas.
☒ Outside urban areas (suburban).

1-7 Regarding mono functionality, the crossing roads are designed as a:
(Multiple answers possible, indicate the roads with numbers on a map)
O Freeway: flow function, serves to let high volumes of traffic flow
☒ Arterial: exchanges traffic from collector roads to freeways
O Collector/distributor: exchanges traffic from local roads to arterials
O Local road: exchange function, serves to give access to residences
O Gray road: road has a flow and exchange function

1-8 Do the American traffic rules according to the traffic signs correspond to the actual function of the traffic system?
☒ Yes.
O No.
O N/a (the traffic rules are not unambiguously determined by present traffic signs)

1-9 Do the Dutch traffic rules according to the traffic signs correspond to the actual function of the traffic system?
☒ Yes.
O No.

O N/a (the traffic rules are not unambiguously determined by present traffic signs)

Additional explanation:
Max. speed is 45 mph (70 km/h) on both roads.
Both intersecting roads are designed as arterials (70 km/h). Road 2 provides access to industrial and business parks. This is done via separate auxiliary lanes. This makes it possible to drive 70 km/h on the through lanes. This can be done based on both Dutch and American guidelines.

In the Netherlands, both roads would be categorized as suburban arterials with a maximum speed of 80 km/h. In this case a physically separated sidewalk should be used, according to Dutch guidelines. Regarding the principle of functionality, this is the only modification that is necessary to make the traffic system meet the set of requirements for this Sustainable Safety principle.

(Bio)mechanica

This principle is in twofold. Firstly, it is related to the homogenization of the traffic system, meaning that limiting the differences in speed, direction, mass and size is desired, and giving road users appropriate protection. Secondly, physical forgiveness of the traffic system is taken into account. This is related to aspects such as whether there is enough space on the road in case maneuvers by road users is required, or to certain objects which may block the road or view. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

Homogenization

2-1 What are the speed limits on the crossing roads?
Major road: 45 mph (70 km/h) **road 1**
Side street: 45 mph (70 km/h) **road 2**

2-2 What are the types of road users that are present at the location? (Multiple answers possible)
X Pedestrians. **Only road 1**
O Bicycles/mopeds
X Motorcycles/cars/vans
X Trucks
O Public transport, such as: …

2-3 Regarding the whole traffic system, are there any possibilities for conflicts between slow traffic and motorized traffic?
O Yes.
X Only potential. For example, when red traffic lights are (intentionally/unintentionally) ignored. Potential conflicts could also occur when slow and motorized traffic are not physically separated.
O No, due to physical separation of slow and motorized vehicles, possibilities of conflicts are very unlikely.

2-4 Are there possibilities for transverse conflicts between motorized traffic on the road?
O Yes.
X Potential conflicts are possible, for example, when red traffic lights are (intentionally/unintentionally) ignored.
O No.

2-5 When excluding the intersections/interchanges, are there possibilities for frontal conflicts between motorized traffic within the traffic system?
O Yes, for example when vehicles overtake.
O Only potential. For example, when (intentionally/unintentionally) crossing the center road marking that divides two-way traffic.
X No, due to physical separation, possibilities of frontal conflicts are very unlikely.

2-6 On places with (potential) conflicts between cyclists/pedestrians and motorized traffic, the speed of motorized traffic is limited to approximately 30 km/h:
O Yes (or n/a).

O No, but these conflicts do not occur regularly, and the speed does not exceed about 50 km/h.
X No, these conflicts occur at higher speeds.

2-7 On one of the intersecting road sections and intersections with potential crossing conflicts between motorized vehicles, the speed of motorized traffic is limited to approximately 50 km/h:
O Yes (or n/a).
X No, but these conflicts do not occur regularly, and the speed does not exceed about 70 km/h.
O No, these conflicts occur at higher speeds.

2-8 On one of the intersecting road sections with (potential) frontal conflicts, the speed of motorized traffic is limited to approximately 70 km/h:
X Yes (or n/a).
O No, but these conflicts do not occur regularly, and the speed does not exceed about 80 km/h.
O No, these conflicts occur at higher speeds.

Physical forgiveness
2-9 Regarding physical forgiveness, the physical boundaries of roadways are designed in such a way that a sufficient width has been used for narrow-paved shoulders:
X Yes (or n/a).
O Approximately. There is some space available for narrow-paved shoulders, but it is not as wide as prescribed in the (Dutch or American) design guidelines.
O No, but it is desired to have narrow-paved shoulders.

2-10 Stopping sight: What is the approximate minimum available sight that is needed to be able to come to a stop in time for discontinuities such as intersections, obstacles, or stationary traffic?

200+ meters

2-11 Driveway sight: What is the approximate minimum available sight for traffic to know if they can cross the road without interfering with crossing traffic, when standing 5 meters before the intersection?

170 meters

Additional explanation:
Potential conflicts can only occur with red light negation. Furthermore, Table 31 (SWOV, 2018) and Table 35 (CROW, 2013) indicate that the sight distances comply with the Dutch guidelines. Regarding the principle of (bio)mechanics, the traffic system meets the requirements set for this principle in the field of Sustainable Safety.

Psychology

Psychology is related to how well the traffic system is designed in a way that especially older road users are capable of recognizing how to safely participate in traffic. This means that even for them the information from the traffic system should be observable, self-explaining, credible, relevant, and executable. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

3-1 What type of lanes are present on the roads? Indicate the road numbers on a map. (Multiple answers possible)

Road 1	Road 2	Road 3
☒ Traffic lane	☒ Traffic lane	O Traffic lane
☒ Hard shoulder	☒ Hard shoulder	O Hard shoulder
☒ Auxiliary lane	☒ Auxiliary lane	O Auxiliary lane
O Truckway	O Truckway	O Truckway
O Bus lane	O Bus lane	O Bus lane
O Bicycle lane	O Bicycle lane	O Bicycle lane
☒ Sidewalk	O Sidewalk	O Sidewalk
☒ Clear zones	☒ Clear zones	O Clear zones
O Others:	O Others:	O Others:

Use Table 32 in the appendix to determine whether the width of each lane type complies with the American and Dutch design guidelines.

3-2 Are these lanes according to the American guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Road 1

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines
Traffic lane	3.60	3.0 to 3.60	Yes.
Hard shoulder	0.60 (narrow-paved shoulder)	0.30 to 0.60	Yes.
Auxiliary lane	3.60	3.0 to 4.80	Yes.
Sidewalk (minimum)	1.70	1.50	Yes.
Clear zone (minimum)	6.0	3.0	Yes.

Road 2

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines
Traffic lane	3.0	3.0 to 3.60	Yes.
Hard shoulder	0.60 (narrow-paved shoulder)	0.30 to 0.60	Yes.

Auxiliary lane	3.0	3.0 to 4.80	Yes.
Clear zone (minimum)	6.0	3.0	Yes.

3-3 Are these lanes according to the Dutch guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Road 1

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines
Traffic lane	3.60	3.0 to 3.10	No.
Hard shoulder	0.60 (narrow-paved shoulder)	0.30	No.
Auxiliary lane	3.60	3.0	No.
Sidewalk (minimum)	1.70	1.50	Yes.
Clear zone (minimum)	6.0	4.50	Yes.

Road 2

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines
Traffic lane	3.0	3.0 to 3.10	Yes.
Hard shoulder	0.60 (narrow-paved shoulder)	0.30	No.
Auxiliary lane	3.0	3.0	Yes.
Clear zone (minimum)	6.0	4.50	Yes.

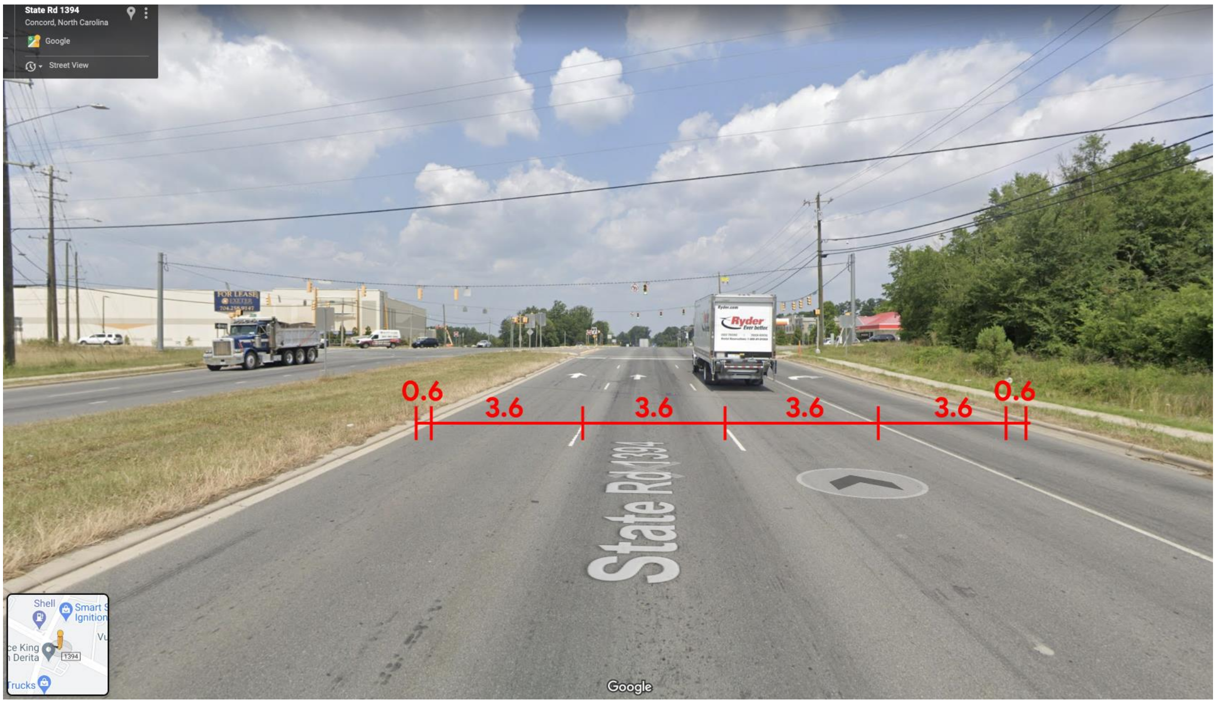


Figure 79 All lane types that do not comply with the Dutch guidelines.

3-4 When road markings are obstructed due to snow, to what extent can the intersection/interchange confuse the road user?

O It will not confuse the road users. For example, due to physically separated roads/lanes.

☒ Potential confusion only among motorized vehicles. Only road signs will help the vehicles navigate through the intersection/interchange.

O Possibilities of severe accidents.

Additional explanation:
The widths of different types of lanes were tested based on the American and Dutch design guidelines. Both intersecting roads comply with American guidelines. However, a number of adjustments are necessary on the basis of the Dutch guidelines. The (auxiliary) lanes are too wide and may only be 3.0 to 3.10 meters wide. The narrow-paved shoulders should also be less wide. A width of 0.3 meters applies to arterial roads.

Heavy snowfall obstructing road markings can cause confusion. Especially for road users who are not familiar with the intersection design. In this case, only road signs are provided to assist drivers in navigating the intersection. It is therefore recommended to get the lines visible in time.

All in all, regarding the principle of psychology, the traffic system meets the requirements set for this principle in the field of Sustainable Safety, provided that a number of plausible adjustments are made to the widths of road lanes.

Desk investigation Sustainable Safety location 2 – Quadrant Roadway

0-1 Using a picture, show the intersection/interchange and number each road (section).

Location: State Route 4 at State Route 4 Bypass/Ross Road, Fairfield, Ohio.

Figure 80 State Route 4 at State Route 4 Bypass/Ross Road, Fairfield, Ohio.

Functionality

The first four questions determine the functionality of the traffic system based on the geometry. The other two questions determine the functionality on the basis of traffic signs present at the location. Traffic signs that may be present are also depicted in the question. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

1-1 Which parts of the infrastructure are designed to let traffic flow? (Multiple answers possible)

O One of the intersecting roads: separate lanes per direction, slow traffic and fast traffic are separated.

O Interchanges: exchanging traffic to surrounding areas while maintaining an ongoing traffic flow.
☒ None of the above.

1-2 Which parts of the infrastructure are designed to exchange traffic? (Multiple answers possible)
☒ One of the intersecting roads: provides access to nearby destinations.
☒ Intersections: Exchanging traffic at-grade with the surroundings.
O None of the above.

1-3 Which parts of the nearby roads are designed on a residential function? (Multiple answers possible)
☒ The residential area is located next to one of the intersecting roads.
O One of the intersecting roads has a mixed residential and traffic function (no separate roadways).
O None of the above.

1-4 Is there a transition of road type on any of the nearby roads?
☒ Yes.
O No.

1-5 What type of traffic signs are used?

☒ 

(25 speed limit, stop and yield signs) (Erftoegangsweg) → Local road **Road section 2.1.**

O 

(speed limit 30 and warning pedestrian crossing) (Gebiedsontsluitingsweg binnen de bebouwde kom) → Collector/distributor

☒ 

(speed limit 40 and boulevard signs) (Gebiedsontsluitingsweg buiten de bebouwde kom) →Arterial **All roads except road section 2.1.**

O 

(speed limit 80 and interstate route signs) (Stroomweg) → Freeway

O None of the above

1-6 Are one of the intersection roads (according to the traffic signs) located inside or outside urban areas?
O Inside urban areas.
☒ Outside urban areas (suburban).

1-7 Regarding mono functionality, the crossing roads are designed as a:
(Multiple answers possible, indicate the roads with numbers on a map)

O Freeway: flow function, serves to let high volumes of traffic flow.

X Arterial: exchanges traffic from collector roads to freeways. **All roads except road section 2.1.**

O Collector/distributor: exchanges traffic from local roads to arterials.

X Local road: exchange function, serves to give access to residences. **Road section 2.1.**

O Gray road: road has a flow and exchange function.

1-8 Do the American traffic rules according to the traffic signs correspond to the actual function of the traffic system?

X Yes.

O No.

O N/a (the traffic rules are not unambiguously determined by present traffic signs)

1-9 Do the Dutch traffic rules according to the traffic signs correspond to the actual function of the traffic system?

X Yes.

O No.

O N/a (the traffic rules are not unambiguously determined by present traffic signs)

Additional explanation:
Road section 2.1 is located within an urban area and provides access to residentials. The other road sections lie within suburban areas and exchange traffic in a higher order. The traffic signs present correspond to the actual function of the road sections. Regarding the principle of functionality, the traffic system complies with the American and Dutch guidelines, and therefore also with the requirements set in the field of Sustainable Safety.

(Bio)mechanica

This principle is in twofold. Firstly, it is related to the homogenization of the traffic system, meaning that limiting the differences in speed, direction, mass and size is desired, and giving road users appropriate protection. Secondly, physical forgiveness of the traffic system is taken into account. This is related to aspects such as whether there is enough space on the road in case maneuvers by road users is required, or to certain objects which may block the road or view. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

Homogenization

2-1 What are the speed limits on the crossing roads?
Major road: 50 mph (80 km/h) **all roads except road section 2.1**
Side street: 25 mph (40 km/h) **road section 2.1**

2-2 What are the types of road users that are present at the location? (Multiple answers possible)
X Pedestrians. **Only road 1**
O Bicycles/mopeds
X Motorcycles/cars/vans
X Trucks
O Public transport, such as: …

2-3 Regarding the whole traffic system, are there any possibilities for conflicts between slow traffic and motorized traffic?
O Yes.
O Only potential. For example, when red traffic lights are (intentionally/unintentionally) ignored. Potential conflicts could also occur when slow and motorized traffic are not physically separated.
X No, due to physical separation of slow and motorized vehicles, possibilities of conflicts are very unlikely.

2-4 Are there possibilities for transverse conflicts between motorized traffic on the road?
O Yes.
X Potential conflicts are possible, for example, when red traffic lights are (intentionally/unintentionally) ignored.
O No.

2-5 When excluding the intersections/interchanges, are there possibilities for frontal conflicts between motorized traffic within the traffic system?
O Yes, for example when vehicles overtake.
X Only potential. For example, when (intentionally/unintentionally) crossing the center road marking that divides two-way traffic.
O No, due to physical separation, possibilities of frontal conflicts are very unlikely.

2-6 On places with (potential) conflicts between cyclists/pedestrians and motorized traffic, the speed of motorized traffic is limited to approximately 30 km/h:
X Yes (or n/a).

O	No, but these conflicts do not occur regularly, and the speed does not exceed about 50 km/h.

O	No, these conflicts occur at higher speeds.

2-7	On one of the intersecting road sections and intersections with potential crossing conflicts between motorized vehicles, the speed of motorized traffic is limited to approximately 50 km/h:

O	Yes (or n/a).

O	No, but these conflicts do not occur regularly, and the speed does not exceed about 70 km/h.

X	No, these conflicts occur at higher speeds.

2-8	On one of the intersecting road sections with (potential) frontal conflicts, the speed of motorized traffic is limited to approximately 70 km/h:

O	Yes (or n/a).

X	No, but these conflicts do not occur regularly, and the speed does not exceed about 80 km/h.

O	No, these conflicts occur at higher speeds.

Physical forgiveness

2-9	Regarding physical forgiveness, the physical boundaries of roadways are designed in such a way that a sufficient width has been used for narrow-paved shoulders:

X	Yes (or n/a).

O	Approximately. There is some space available for narrow-paved shoulders, but it is not as wide as prescribed in the (Dutch or American) design guidelines.

O	No, but it is desired to have narrow-paved shoulders.

2-10	Stopping sight: What is the approximate minimum available sight that is needed to be able to come to a stop in time for discontinuities such as intersections, obstacles, or stationary traffic?

190 meters

2-11	Driveway sight: What is the approximate minimum available sight for traffic to know if they can cross the road without interfering with crossing traffic, when standing 5 meters before the intersection?

185 meters

Additional explanation:
Potential conflicts can only occur with red light negation and when the direction marker is crossed consciously or unconsciously. Furthermore, Table 31 (SWOV, 2018), Table 34 and Table 35 (CROW, 2013) indicate that the sight distances comply with the Dutch guidelines. Regarding the principle of (bio)mechanics, the traffic system meets the requirements set for this principle in the field of Sustainable Safety.

Psychology

Psychology is related to how well the traffic system is designed in a way that especially older road users are capable of recognizing how to safely participate in traffic. This means that even for them the information from the traffic system should be observable, self-explaining, credible, relevant, and executable. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

3-1 What type of lanes are present on the roads? Indicate the road numbers on a map. (Multiple answers possible)

Road 1	**Road 2**	**Road 3**
X Traffic lane	X Traffic lane	O Traffic lane
X Hard shoulder	X Hard shoulder	X Hard shoulder
X Auxiliary lane	X Auxiliary lane	X Auxiliary lane
O Truckway	O Truckway	O Truckway
O Bus lane	O Bus lane	O Bus lane
O Bicycle lane	O Bicycle lane	O Bicycle lane
O Sidewalk	X Sidewalk	O Sidewalk
X Clear zones	X Clear zones	X Clear zones
O Others:	O Others:	O Others:

Use Table 32 in the appendix to determine whether the width of each lane type complies with the American and Dutch design guidelines.

3-2 Are these lanes according to the American guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Road 1

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines
Traffic lane	3.20	3.0 to 3.60	Yes.
Hard shoulder	- 0.30 (narrow-paved shoulder) - 3.0 (emergency lane)	- 0.30 to 0.60 - 3.0 to 3.60	Yes.
Auxiliary lane	3.20	3.0 to 4.80	Yes.
Clear zone (minimum)	6.0	3.0	Yes.

Road section 2.1

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines
Traffic lane	3.0	3.0 to 3.30	Yes.
Hard shoulder	0.60 (narrow-paved shoulder)	0.30 to 0.60	Yes.
Auxiliary lane	3.0	3.0 to 4.80	Yes.

Sidewalk (minimum)	1.50	1.50	Yes.
Clear zone (minimum)	6.0	2.0	Yes.

Road sections 2.2 en 2.3

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines
Traffic lane	3.20	3.0 to 3.60	Yes.
Hard shoulder	3.0 (emergency lane)	3.0 to 3.60	Yes.
Auxiliary lane	3.10	3.0 to 4.80	Yes.
Clear zone (minimum)	6.0	3.0	Yes.

Weg 3

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines
Hard shoulder	2.30 (emergency lane)	1.80 to 2.40	Yes.
Auxiliary lane	4.0	3.0 to 4.80	Yes.
Clear zone (minimum)	6.0	3.0	Yes.

3-3 Are these lanes according to the Dutch guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Road 1

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines
Traffic lane	3.20	3.0 to 3.10	Yes.
Hard shoulder	- 0.30 (narrow-paved shoulder) - 3.0 (emergency lane)	- 0.30 - 3.0 to 3.60	Yes.
Auxiliary lane	3.20	3.0	Yes.
Clear zone (minimum)	6.0	4.50	Yes.

Road section 2.1

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines
Traffic lane	3.0	3.0 to 3.10	Yes.
Hard shoulder	0.60 (narrow-paved shoulder)	0.30	No.

Auxiliary lane	3.0	3.0	Yes.
Sidewalk (minimum)	1.50	1.50	Yes.
Clear zone (minimum)	6.0	3.0	Yes.

Road sections 2.2 en 2.3

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines
Traffic lane	3.20	3.0 to 3.10	No. (Negligible)
Hard shoulder	3.0 (emergency lane)	3.0 to 3.60	Yes.
Auxiliary lane	3.10	3.0	Yes.
Clear zone (minimum)	6.0	4.50	Yes.

Weg 3

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines
Hard shoulder	2.30 (emergency lane)	3.0 to 3.60	No.
Auxiliary lane	4.0	3.0 to 3.10	No.
Clear zone (minimum)	6.0	4.50	Yes.

Figure 81 All lane types that do not comply with the Dutch guidelines.

3-4 When road markings are obstructed due to snow, to what extent can the intersection/interchange confuse the road user?

O It will not confuse the road users. For example, due to physically separated roads/lanes.

X Potential confusion only among motorized vehicles. Only road signs will help the vehicles navigate through the intersection/interchange.

O Possibilities of severe accidents.

Additional explanation:
The Quadrant Roadway on location 2 has been completely designed and constructed according to American guidelines. When the comparison is made with the Dutch guidelines, there are a number of lanes present that do not comply with this.

Here too, the Narrow-paved shoulders should be less wide. A width of 0.30 meters applies to arterials.

Furthermore, the width of the lane on road section 2.2 is 10 centimeters too short, however, this is negligible.

Road section 3, the connecting road, can be seen as a turn. The lanes on this road section are too wide. According to the CROW (2002), an extra widening of these curves of 0.50 meters per lane must be taken into account. Even with the extra width, the lanes do not meet the Dutch guidelines.

On the other hand, the emergency lane on road section 3 is too narrow and therefore does not comply with Dutch guidelines. Low intensity traffic is believed to be present on the connector road of the Quadrant Roadway. This is only intended for left-turning traffic. Through traffic generally has a higher traffic intensity. For this reason, the width of the emergency lane differs from that on the connector road with the surrounding roads. These emergency lanes are also constructed to support diverting freight traffic by giving them extra space to take the turn. All in all, regarding the principle of psychology, the traffic system meets the requirements set for this principle in the field of Sustainable Safety, provided that a number of plausible adjustments are made to the widths of road lanes.

Desk investigation Sustainable Safety location 3 – Diverging Diamond Interchange

0-1 Using a picture, show the intersection/interchange and number each road (section).

Location: I-64 at U.S. 15 (James Madison Hwy), Zion Crossroads, Va.

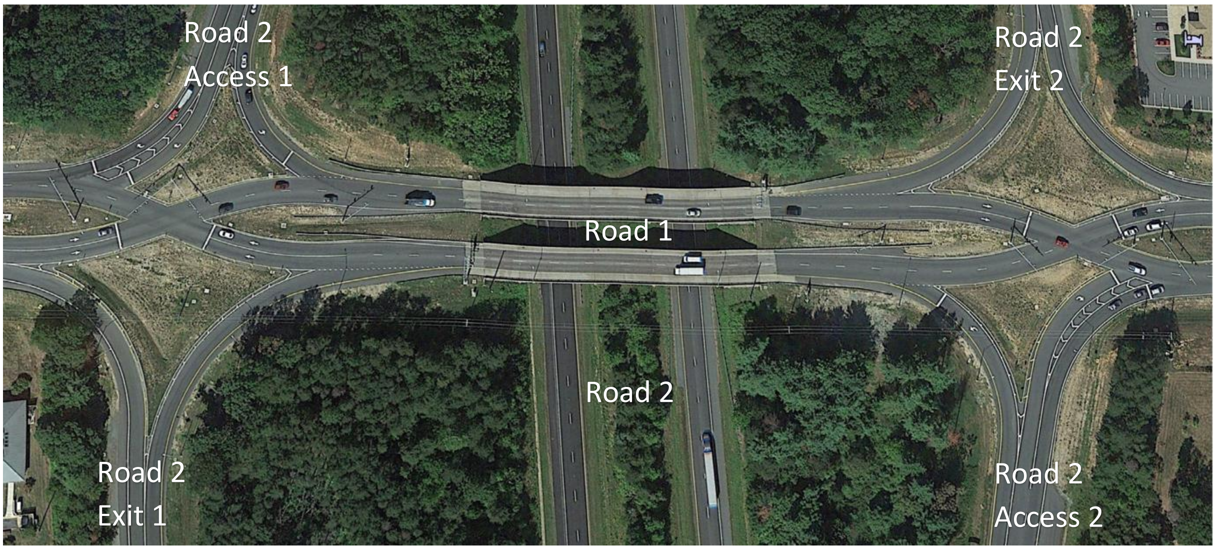


Figure 82 I-64 at U.S. 15 (James Madison Hwy), Zion Crossroads, Va.

Functionality

The first four questions determine the functionality of the traffic system based on the geometry. The other two questions determine the functionality on the basis of traffic signs present at the location. Traffic signs that may be present are also depicted in the question. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

1-1 Which parts of the infrastructure are designed to let traffic flow? (Multiple answers possible)

O One of the intersecting roads: separate lanes per direction, slow traffic and fast traffic are separated.

⊗ Interchanges: exchanging traffic to surrounding areas while maintaining an ongoing traffic flow.

O None of the above.

1-2 Which parts of the infrastructure are designed to exchange traffic? (Multiple answers possible)

⊗ One of the intersecting roads: provides access to nearby destinations.

⊗ Intersections: Exchanging traffic at-grade with the surroundings.

O None of the above.

1-3 Which parts of the nearby roads are designed on a residential function? (Multiple answers possible)

O The residential area is located next to one of the intersecting roads.
O One of the intersecting roads has a mixed residential and traffic function (no separate roadways).
☒ None of the above.

1-4 Is there a transition of road type on any of the nearby roads?

☒ Yes.
O No.

1-5 What type of traffic signs are used?

O 

(25 speed limit, stop and yield signs) (Erftoegangsweg) → Local road

O 

(speed limit 30 and warning pedestrian crossing) (Gebiedsontsluitingsweg binnen de bebouwde kom) → Collector/distributor

☒ 

(speed limit 40 and boulevard signs) (Gebiedsontsluitingsweg buiten de bebouwde kom) →Arterial **Road 1**

☒ 

(speed limit 80 and interstate route signs) (Stroomweg) → Freeway **Road 2**

O None of the above

1-6 Are one of the intersection roads (according to the traffic signs) located inside or outside urban areas?

O Inside urban areas.
☒ Outside urban areas (suburban).

1-7 Regarding mono functionality, the crossing roads are designed as a: (Multiple answers possible, indicate the roads with numbers on a map)

☒ Freeway: flow function, serves to let high volumes of traffic flow. **Road 2**
☒ Arterial: exchanges traffic from collector roads to freeways. **Road 1**
O Collector/distributor: exchanges traffic from local roads to arterials.
O Local road: exchange function, serves to give access to residences.
O Gray road: road has a flow and exchange function.

1-8 Do the American traffic rules according to the traffic signs correspond to the actual function of the traffic system?

☒ Yes.
O No.
O N/a (the traffic rules are not unambiguously determined by present traffic signs)

1-9 Do the Dutch traffic rules according to the traffic signs correspond to the actual function of the traffic system?

X Yes.

O No.

O N/a (the traffic rules are not unambiguously determined by present traffic signs)

Additional explanation:
N/a.

(Bio)mechanica

This principle is in twofold. Firstly, it is related to the homogenization of the traffic system, meaning that limiting the differences in speed, direction, mass and size is desired, and giving road users appropriate protection. Secondly, physical forgiveness of the traffic system is taken into account. This is related to aspects such as whether there is enough space on the road in case maneuvers by road users is required, or to certain objects which may block the road or view. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

Homogenization

2-1 What are the speed limits on the crossing roads?
Major road: 70 mph (110 km/h) **road 2**
Side street: 30 mph (50 km/h). After the intersection, speed increases to 45 mph (70 km/h) **road 1**

2-2 What are the types of road users that are present at the location? (Multiple answers possible)
O Pedestrians.
O Bicycles/mopeds
X Motorcycles/cars/vans
X Trucks
O Public transport, such as: …

2-3 Regarding the whole traffic system, are there any possibilities for conflicts between slow traffic and motorized traffic?
O Yes.
O Only potential. For example, when red traffic lights are (intentionally/unintentionally) ignored. Potential conflicts could also occur when slow and motorized traffic are not physically separated.
X No, due to physical separation of slow and motorized vehicles, possibilities of conflicts are very unlikely.

2-4 Are there possibilities for transverse conflicts between motorized traffic on the road?
O Yes.
X Potential conflicts are possible, for example, when red traffic lights are (intentionally/unintentionally) ignored.
O No.

2-5 When excluding the intersections/interchanges, are there possibilities for frontal conflicts between motorized traffic within the traffic system?
O Yes, for example when vehicles overtake.
O Only potential. For example, when (intentionally/unintentionally) crossing the center road marking that divides two-way traffic.
X No, due to physical separation, possibilities of frontal conflicts are very unlikely.

2-6 On places with (potential) conflicts between cyclists/pedestrians and motorized traffic, the speed of motorized traffic is limited to approximately 30 km/h:

⊗ Yes (or n/a).

O No, but these conflicts do not occur regularly, and the speed does not exceed about 50 km/h.

O No, these conflicts occur at higher speeds.

2-7 On one of the intersecting road sections and intersections with potential crossing conflicts between motorized vehicles, the speed of motorized traffic is limited to approximately 50 km/h:

⊗ Yes (or n/a).

O No, but these conflicts do not occur regularly, and the speed does not exceed about 70 km/h.

O No, these conflicts occur at higher speeds.

2-8 On one of the intersecting road sections with (potential) frontal conflicts, the speed of motorized traffic is limited to approximately 70 km/h:

⊗ Yes (or n/a).

O No, but these conflicts do not occur regularly, and the speed does not exceed about 80 km/h.

O No, these conflicts occur at higher speeds.

Physical forgiveness

2-9 Regarding physical forgiveness, the physical boundaries of roadways are designed in such a way that a sufficient width has been used for narrow-paved shoulders:

⊗ Yes (or n/a).

O Approximately. There is some space available for narrow-paved shoulders, but it is not as wide as prescribed in the (Dutch or American) design guidelines.

O No, but it is desired to have narrow-paved shoulders.

2-10 Stopping sight: What is the approximate minimum available sight that is needed to be able to come to a stop in time for discontinuities such as intersections, obstacles, or stationary traffic?

50+ meters

2-11 Driveway sight: What is the approximate minimum available sight for traffic to know if they can cross the road without interfering with crossing traffic, when standing 5 meters before the intersection?

100+ meters

Additional explanation:
Potential conflicts can only occur with red light negation. Furthermore, Table 31 (SWOV, 2018) and Table 35 (CROW, 2013) indicate that the sight distances comply with the Dutch guidelines. Regarding the principle of (bio)mechanics, the traffic system meets the requirements set for this principle in the field of Sustainable Safety.

Psychology

Psychology is related to how well the traffic system is designed in a way that especially older road users are capable of recognizing how to safely participate in traffic. This means that even for them the information from the traffic system should be observable, self-explaining, credible, relevant, and executable. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

3-1 What type of lanes are present on the roads? Indicate the road numbers on a map. (Multiple answers possible)[3]

Road 1	Road 2	Road 3
X Traffic lane	O Traffic lane	O Traffic lane
X Hard shoulder	O Hard shoulder	O Hard shoulder
X Auxiliary lane	O Auxiliary lane	O Auxiliary lane
O Truckway	O Truckway	O Truckway
O Bus lane	O Bus lane	O Bus lane
O Bicycle lane	O Bicycle lane	O Bicycle lane
O Sidewalk	O Sidewalk	O Sidewalk
X Clear zones	O Clear zones	O Clear zones
O Others:	O Others:	O Others:

Use Table 32 in the appendix to determine whether the width of each lane type complies with the American and Dutch design guidelines.

3-2 Are these lanes according to the American guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Road 1

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines
Traffic lane	3.60	3.0 to 3.60	Yes.
Hard shoulder	0.60 (narrow-paved shoulder)	0.30 to 0.60	Yes.
Auxiliary lane	3.60	3.0 to 4.80	Yes.
Clear zone (minimum)	6.0	2.0	Yes.

3-3 Are these lanes according to the Dutch guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Road 1

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines
Traffic lane	3.60	3.0 to 3.10	No.
Hard shoulder	0.60 (narrow-paved shoulder)	0.30	No.

[3] Road 2 is a highway and is disregarded. The design of the highway falls outside the scope of this study.

Auxiliary lane	3.60	3.0	No.
Clear zone (minimum)	6.0	3.0	Yes.

3-4 When road markings are obstructed due to snow, to what extent can the intersection/interchange confuse the road user?

O It will not confuse the road users. For example, due to physically separated roads/lanes.

☒ Potential confusion only among motorized vehicles. Only road signs will help the vehicles navigate through the intersection/interchange.

O Possibilities of severe accidents.

Figure 83 All lane types (except narrow-paved shoulder on the right side) that do not comply with the Dutch guidelines.

Additional explanation:
Road 2 is a highway. This was disregarded because the design of the highway falls outside the scope of this study. Only the fact that a highway is present is taken into account. The (alternative) lanes are too wide and may only be 3.0 to 3.10 meters wide. The narrow-paved shoulders should also be less wide. A width of 0.30 meters applies to arterials.

Heavy snowfall obstructing road markings can cause confusion. This is especially true for the crossovers. In this case, only traffic road signs are provided to assist drivers in navigating the intersection. It is therefore recommended to make the road markings visible in time.

All in all, with regard to the principle of psychology, the traffic system meets the requirements set for this principle in the field of Sustainable Safety, provided that a number of plausible adjustments are made to the widths of road lanes.

0-1 Using a picture, show the intersection/interchange and number each road (section).

Location: U.S. 50 (Arlington Boulevard) at Gallows Road, Falls Church, Va.

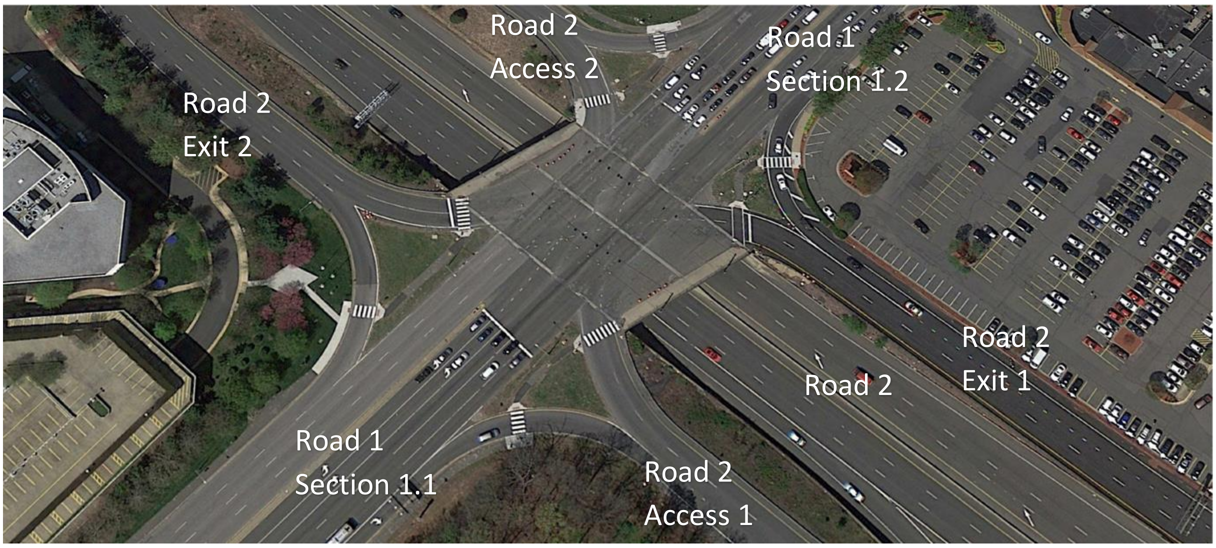


Figure 1 U.S. 50 (Arlington Boulevard) at Gallows Road, Falls Church, Va.

Functionality

The first four questions determine the functionality of the traffic system based on the geometry. The other two questions determine the functionality on the basis of traffic signs present at the location. Traffic signs that may be present are also depicted in the question. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

1-1 Which parts of the infrastructure are designed to let traffic flow? (Multiple answers possible)

O One of the intersecting roads: separate lanes per direction, slow traffic and fast traffic are separated.

⊠ Interchanges: exchanging traffic to surrounding areas while maintaining an ongoing traffic flow.

O None of the above.

1-2 Which parts of the infrastructure are designed to exchange traffic? (Multiple answers possible)

⊠ One of the intersecting roads: provides access to nearby destinations.

⊠ Intersections: Exchanging traffic at-grade with the surroundings.

O None of the above.

1-3 Which parts of the nearby roads are designed on a residential function? (Multiple answers possible)

☒ The residential area is located next to one of the intersecting roads.

☒ One of the intersecting roads has a mixed residential and traffic function (no separate roadways).

O None of the above.

1-4 Is there a transition of road type on any of the nearby roads?

☒ Yes.

O No.

1-5 What type of traffic signs are used?

O 

(25 speed limit, stop and yield signs) (Erftoegangsweg) → Local road

☒ 

(speed limit 30 and warning pedestrian crossing) (Gebiedsontsluitingsweg binnen de bebouwde kom) → Collector/distributor **Road 1**

☒ 

(speed limit 40 and boulevard signs) (Gebiedsontsluitingsweg buiten de bebouwde kom) → Arterial **Road 2**

O 

(speed limit 80 and interstate route signs) (Stroomweg) → Freeway

O None of the above

1-6 Are one of the intersection roads (according to the traffic signs) located inside or outside urban areas?

O Inside urban areas.

☒ Outside urban areas (suburban).

1-7 Regarding mono functionality, the crossing roads are designed as a: (Multiple answers possible, indicate the roads with numbers on a map)

O Freeway: flow function, serves to let high volumes of traffic flow.

☒ Arterial: exchanges traffic from collector roads to freeways. **Road 2**

☒ Collector/distributor: exchanges traffic from local roads to arterials. **Road 1**

O Local road: exchange function, serves to give access to residences.

O Gray road: road has a flow and exchange function.

1-8 Do the American traffic rules according to the traffic signs correspond to the actual function of the traffic system?

☒ Yes.

O No.

O N/a (the traffic rules are not unambiguously determined by present traffic signs)

1-9 Do the Dutch traffic rules according to the traffic signs correspond to the actual function of the traffic system?

X Yes.

O No.

O N/a (the traffic rules are not unambiguously determined by present traffic signs)

Additional explanation:
Road 1 provides access to adjacent business parks and is a collector/distributor. Here, a maximum speed of 35 mph (55 km/h) applies. There is a maximum speed of 45 mph (70 km/h) on road 2. This road exchanges traffic ahead with a higher order highway (interstate highway 495). For this reason, this is an arterial. A maximum speed of 35 mph (55 km/h) applies to the exits, which corresponds to road 1. Regarding the principle of functionality, the traffic system complies with the American and Dutch guidelines, and therefore also with the requirements set in the area. of Sustainably Safe.

(Bio)mechanica

This principle is in twofold. Firstly, it is related to the homogenization of the traffic system, meaning that limiting the differences in speed, direction, mass and size is desired, and giving road users appropriate protection. Secondly, physical forgiveness of the traffic system is taken into account. This is related to aspects such as whether there is enough space on the road in case maneuvers by road users is required, or to certain objects which may block the road or view. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

Homogenization

2-1 What are the speed limits on the crossing roads?
Major road: 45 mph (70 km/h) **road 2**
Side street and exists: 35 mph (55 km/h) **road 1 and road 2 exits**

2-2 What are the types of road users that are present at the location? (Multiple answers possible)
X Pedestrians. **Only road 1**
O Bicycles/mopeds
X Motorcycles/cars/vans
X Trucks
O Public transport, such as: …

2-3 Regarding the whole traffic system, are there any possibilities for conflicts between slow traffic and motorized traffic?
O Yes.
X Only potential. For example, when red traffic lights are (intentionally/unintentionally) ignored. Potential conflicts could also occur when slow and motorized traffic are not physically separated.
O No, due to physical separation of slow and motorized vehicles, possibilities of conflicts are very unlikely.

2-4 Are there possibilities for transverse conflicts between motorized traffic on the road?
O Yes.
X Potential conflicts are possible, for example, when red traffic lights are (intentionally/unintentionally) ignored.
O No.

2-5 When excluding the intersections/interchanges, are there possibilities for frontal conflicts between motorized traffic within the traffic system?
O Yes, for example when vehicles overtake.
O Only potential. For example, when (intentionally/unintentionally) crossing the center road marking that divides two-way traffic.
X No, due to physical separation, possibilities of frontal conflicts are very unlikely.

2-6 On places with (potential) conflicts between cyclists/pedestrians and motorized traffic, the speed of motorized traffic is limited to approximately 30 km/h:

O Yes (or n/a).

X No, but these conflicts do not occur regularly, and the speed does not exceed about 50 km/h.

O No, these conflicts occur at higher speeds.

2-7 On one of the intersecting road sections and intersections with potential crossing conflicts between motorized vehicles, the speed of motorized traffic is limited to approximately 50 km/h:

X Yes (or n/a).

O No, but these conflicts do not occur regularly, and the speed does not exceed about 70 km/h.

O No, these conflicts occur at higher speeds.

2-8 On one of the intersecting road sections with (potential) frontal conflicts, the speed of motorized traffic is limited to approximately 70 km/h:

X Yes (or n/a).

O No, but these conflicts do not occur regularly, and the speed does not exceed about 80 km/h.

O No, these conflicts occur at higher speeds.

Physical forgiveness

2-9 Regarding physical forgiveness, the physical boundaries of roadways are designed in such a way that a sufficient width has been used for narrow-paved shoulders:

X Yes (or n/a).

O Approximately. There is some space available for narrow-paved shoulders, but it is not as wide as prescribed in the (Dutch or American) design guidelines.

O No, but it is desired to have narrow-paved shoulders.

2-10 Stopping sight: What is the approximate minimum available sight that is needed to be able to come to a stop in time for discontinuities such as intersections, obstacles, or stationary traffic?

200+ meters

2-11 Driveway sight: What is the approximate minimum available sight for traffic to know if they can cross the road without interfering with crossing traffic, when standing 5 meters before the intersection?

175 meters

Additional explanation:
Potential conflicts can only occur with red light negation. Furthermore, Table 31 (SWOV, 2018) and Table 35 (CROW, 2013) indicate that the sight distances comply with the Dutch guidelines. Regarding the principle of (bio)mechanics, the traffic system meets the requirements set for this principle in the field of Sustainable Safety.

Psychology

Psychology is related to how well the traffic system is designed in a way that especially older road users are capable of recognizing how to safely participate in traffic. This means that even for them the information from the traffic system should be observable, self-explaining, credible, relevant, and executable. **If necessary, name the relevant numbers with the chosen answers. If no specific indication is given, both roads are used.**

3-1 What type of lanes are present on the roads? Indicate the road numbers on a map. (Multiple answers possible)

Road 1	**Road 2**	**Road 3**
☒ Traffic lane	☒ Traffic lane	O Traffic lane
☒ Hard shoulder	☒ Hard shoulder	O Hard shoulder
☒ Auxiliary lane	☒ Auxiliary lane	O Auxiliary lane
O Truckway	O Truckway	O Truckway
O Bus lane	O Bus lane	O Bus lane
O Bicycle lane	O Bicycle lane	O Bicycle lane
☒ Sidewalk	O Sidewalk	O Sidewalk
☒ Clear zones	☒ Clear zones	O Clear zones
O Others:	O Others:	O Others:

Use Table 32 in the appendix to determine whether the width of each lane type complies with the American and Dutch design guidelines.

3-2 Are these lanes according to the American guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Road 1

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines
Traffic lane	3.30	3.0 to 3.30	Yes.
Hard shoulder	- 0.30 (narrow-paved shoulder) - 3.0 (emergency lane)	- 0.30 to 0.60 - 3.0 to 3.60	Yes.
Auxiliary lane	3.60	3.0 to 4.80	Yes.
Sidewalk (minimum)	2.30	1.50	Yes.
Clear zone (minimum)	6.0	2.0	Yes.

Road 2

Lane types	Width (m)	Width according to American guidelines (m)	Complies with the guidelines
Traffic lane	3.60	3.0 to 3.60	Yes.
Hard shoulder	- 1.20 (narrow-paved shoulder) - 3.0 (emergency lane)	- 0.30 to 0.60 - 3.0 to 3.60	No for narrow-paved shoulder. Yes for emergency lane.
Auxiliary lane	3.0	3.0 to 4.80	Yes.
Clear zone (minimum)	6.0	3.0	Yes.

3-3 Are these lanes according to the Dutch guidelines? Add screenshots with additional clarification of the situations if guidelines are not met.

Road 1

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines
Traffic lane	3.30	3.0 tot 3.10	No.
Hard shoulder	- 0.3 (narrow-paved shoulder) - 3.0 (emergency lane)	- 0.30 - 3.0 to 3.60	Yes.
Auxiliary lane	3.60	3.0	No.
Sidewalk (minimum)	2.30	1.50	Yes.
Clear zone (minimum)	6.0	3.0	Yes.

Road 2

Lane types	Width (m)	Width according to Dutch guidelines (m)	Complies with the guidelines
Traffic lane	3.60	3.0 to 3.10	No.
Hard shoulder	- 1.20 (narrow-paved shoulder) - 3.0 (emergency lane)	- 0.30 to 0.60 - 3.0 to 3.60	No for narrow-paved shoulder. Yes for emergency lane.
Auxiliary lane	3.0	3.0	Yes.
Clear zone (minimum)	6.0	4.50	Yes.

Figure 2 Dimensions of an exit that does not comply with the Dutch guidelines.

Figure 3 Dimensions of road 2 that does not comply with the Dutch guidelines.

The figures above show a number of types of lanes that do not meet the Dutch guidelines. The first image is situated on an exit of road 2. The same applies to road 2 itself in Figure 3. For both situations, only the emergency lanes of 3.0 meters meet the Dutch guidelines.

3-4 When road markings are obstructed due to snow, to what extent can the intersection/interchange confuse the road user?

O It will not confuse the road users. For example, due to physically separated roads/lanes.

X Potential confusion only among motorized vehicles. Only road signs will help the vehicles navigate through the intersection/interchange.

O Possibilities of severe accidents.

Additional explanation:
The widths of different types of lanes were tested based on the American and Dutch design guidelines. Both intersecting roads comply with American guidelines. Only the narrow-paved shoulder does not comply on road 2. It is probably extra wide due to the absence of an actual median.

Several adjustments are necessary based on the Dutch guidelines. Road 2 gives the impression of a Dutch highway. This is partly due to the amount of (wide) lanes. The (alternative) lanes are too wide and may only be 3.0 to 3.10 meters wide. The narrow-paved shoulders should also be less wide. A width of 0.30 meters applies to arterials.

Heavy snowfall obstructing road markings can cause confusion at the intersection platform. Especially for road users who are not familiar with the intersection design. In this case, only road signs are provided to assist drivers in navigating the intersection. It is therefore recommended to make the road markings visible in time.

All in all, regarding the principle of psychology, the traffic system meets the requirements set for this principle in the field of Sustainable Safety, provided that a number of plausible adjustments are made to the widths of road lanes.

F
Workshop at the province Noord-Holland

On June 24th, a workshop was held at the province. Twenty-two people were invited, of which eleven were present. The audience consisted of members of different departments and sectors, among which road design, policy, traffic safety, management, and mobility.

The goal of the workshop was, among others, to gain insight in how experts and professionals of the province think of unconventional designs for intersections and interchanges, as they have a different working method at the province. This was done by asking several questions to monitor the prior knowledge of the experts regarding unconventional designs.

Another goal of the workshop was to discuss two cases where these designs (MUT, QR, DDI and SPUI) could be built, to receive expert judgement regarding these designs. Questions were asked for each design whether they thought it would be interesting for further research. The idea behind this question was to gain additional justification of the chosen unconventional designs. When a design was rated positively, a follow-up question was asked. This question corresponds to the third sub question of this study. It was asked, if results from this research would show that a design has a lot of potential in the Netherlands, what are then the next steps you have to take in order to actually build the design? The final question asked was as follows; What chances and potential do you see on provincial roads? This question was asked to find out to what extent the experts and professionals got convinced by the presentation of the potential of the unconventional designs.

Lastly, the workshop was also used to gain additional knowledge which can complement the rest of this research, such as topics that were not considered in this study, prior to this workshop.

The remaining of this chapter discusses the workshop highlights, where the results of the asked questions are shown and described. Hereafter, all the slides of the presentation of the workshop are shown.

Workshop highlights

This section describes the responses of the audience given to the Mentimeter questions, including their argumentations and some final remarks. The next section shows all the slides presented (in Dutch).

First, several questions were asked to monitor the prior knowledge of the experts regarding unconventional designs. Hereafter, the case studies were presented, and questions were asked for each design whether they thought it would be interesting for further research. The idea behind this question per design was to gain additional justification of the chosen unconventional designs. When a design was rated positively, a follow-up question was asked. This question corresponds to the fourth sub question of this study. It was asked, if results from this research would show that a design has a lot of potential in the Netherlands, what are then the next steps you have to take in order to actually build the design? The final question asked was as follows; What chances and potential do you see on provincial roads? This question was asked to find out to what extent the experts and professionals got convinced by the presentation of the potential of the unconventional designs. The answers were given fully anonymously. Therefore, no distinction could be made between the disciplines of the audience.

To what extent are you aware of innovative designs?

Before introducing several examples of unconventional designs, the question was asked whether anyone knew anything about such designs. The results are shown below.

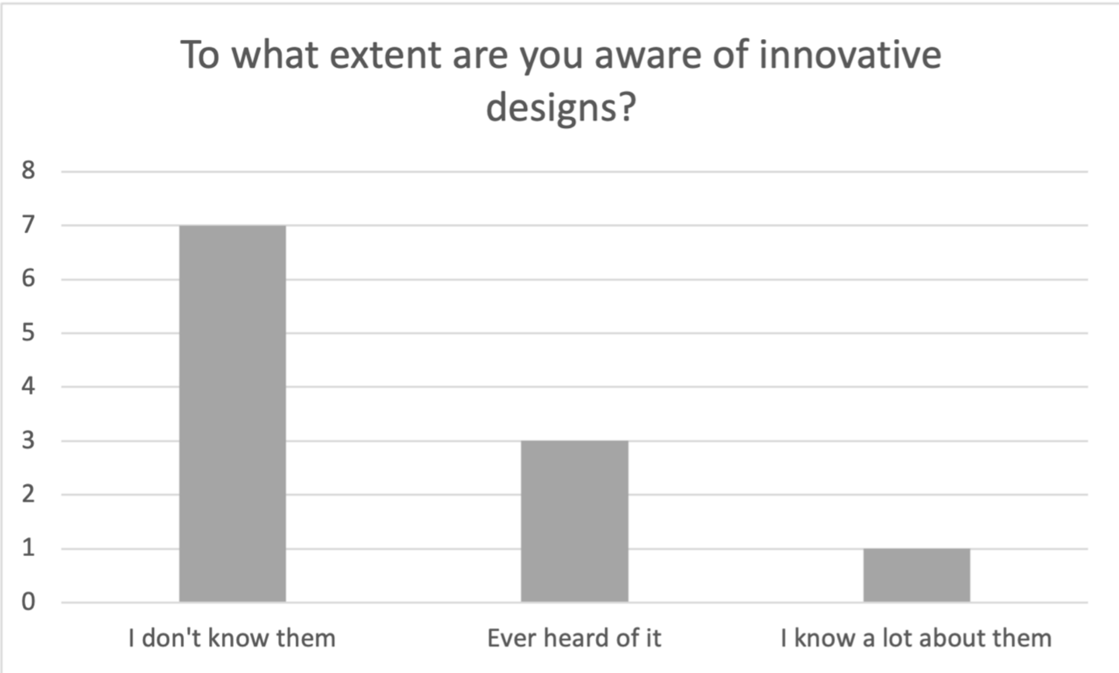


Figure 84 Results question 1: To what extent are you aware of innovative designs?

The majority had never heard of any new designs. On the other hand, one person knew a lot about the Diverging Diamond Interchange, which is an innovative design that was built for the first time in the Netherlands in 2019. Some Dutch innovative designs were mentioned as well, such as the LarGas-roundabout.

Despite the advantages of unconventional designs, why has little attention been paid to it in the Netherlands?

Thereafter, to give the audience an impression of what innovative designs might look like, two designs were discussed, these were the RCUT and Echelon. Then through Mentimeter the question was asked, why there has not been too much attention paid to these types of innovative designs, despite their advantages? It was possible to give multiple answers. The results are shown below.

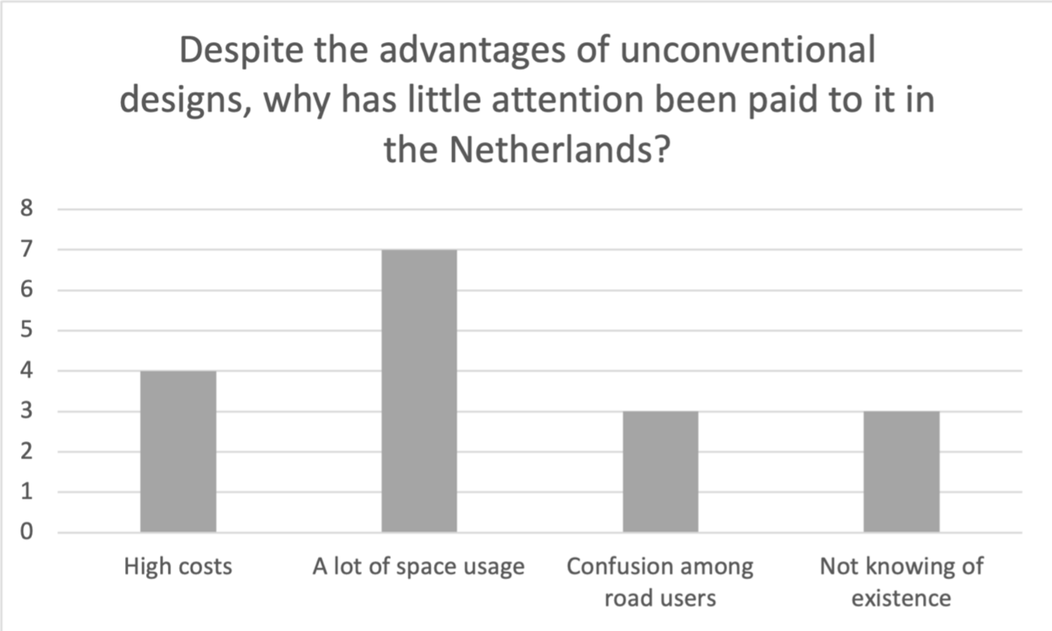


Figure 85 Results question 2: Despite the advantages of unconventional designs, why has little attention been paid to it in the Netherlands?

The majority answered that it might has been due to the heavy use of space. Generally, all the answers were correct in this case, but there are certain designs that do not require a lot of space, nor costs. These would be mentioned later in the workshop.

Why was specifically chosen for the Diverging Diamond Interchange design?

The first American (unconventional) interchange built in the Netherlands, the Diverging Diamond Interchange (DDI), was discussed, including how it works. Then the question was asked why they think the involved road operators and road designers specifically chose for this design. It was possible to give multiple answers. The results are shown below.

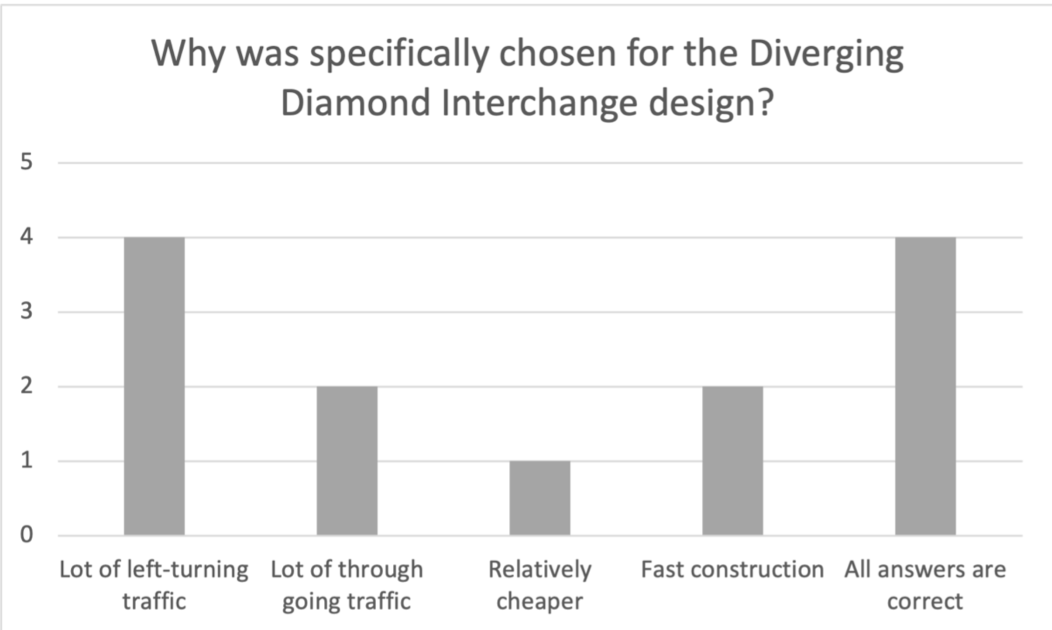


Figure 86 Results question 3: Why was specifically chosen for the Diverging Diamond Interchange design?

The majority knew that this design is used when there is a lot of left-turning traffic present. On the other hand, not many people knew that this design is also cost-efficient. Of course, this is not the main reason the DDI was considered, but it is an important benefit which might have played a role in the decision-making. Regarding the other responses, reference is made to Section 4.3 where the advantages of the DDI are described.

Are the QR and MUT interesting for further research on the first (reference) location?

The first (reference) location was discussed, along with the first alternative, the Quadrant Roadway. This included, the advantages, disadvantages, and the way the design works. Thereafter, the question was asked whether it would be interesting for further research on this first location. A similar way, the MUT was introduced, and the same question was asked. The results are shown below.

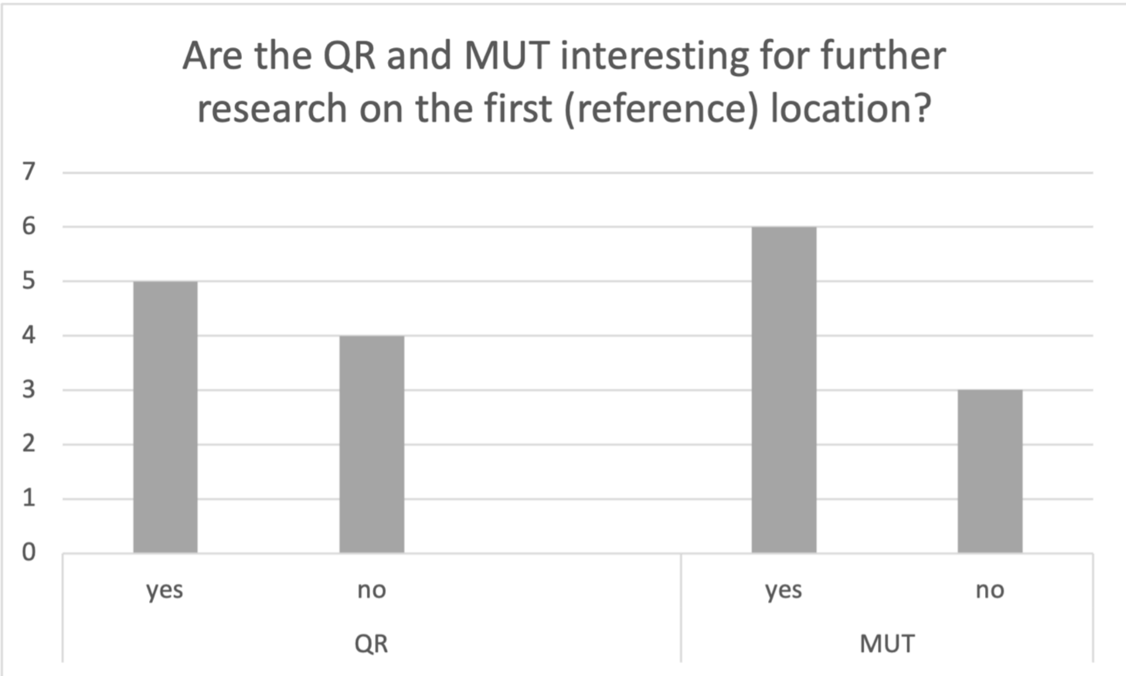


Figure 87 Results question 4 (and 5): Are the QR and MUT interesting for further research on the first (reference) location?

The opinions were divided for the QR. People who voted “no” had the argument that regarding traffic safety, not much changed. The design goes from 32 conflict points on one intersection, to 30 conflict points on three intersections in total (so, 10 per intersection). Therefore, not much benefit regarding traffic safety is observed to justify adding a connector road. Further, mainly the improved traffic flows were reasons why certain experts supported this design.

For the MUT, the majority voted “yes”. Reasons were given as well. They said the MUT has a lot of potential in terms of traffic flow and traffic safety, and that it was a good thing that the U-Turns are signalized. It was also mentioned that the efficient use of space is a great benefit, especially in the Netherlands with the increasing urbanization.
This led to ask a follow-up question to the experts. It was asked, if results from this research would show that this design has a lot of potential in the Netherlands, what are then the next steps you have to take in order to actually build the design? Also, to get the design in the CROW guidelines.

The experts replied by saying “just do it”. It was mentioned that some small studies are necessary on beforehand, such as traffic psychology, to determine how road users experience new infrastructural components such as the U-Turn. Other than that, guts are necessary to build such designs, but you might receive political backlash if the design turns out to be a disaster.

Regarding the way these designs can be added to the CROW guidelines, it might take years. When looking at innovative Dutch designs such as the turbo roundabout and the LarGas-roundabout, despite having a lot of experience, it took years before these designs got added to CROW guidelines.
All these designs started as an idea, where the developers created their own guidelines with sketches. After that it is a matter of time to get it added. However, in the meantime, it is recommended to show guts and do build and test these designs on a small scale.

Are the DDI and SPUI interesting for further research on the second (reference) location?

A similar way, the DDI and SPUI were introduced, and the same question was asked. For the interchange designs another location where they can be built was described. The results are shown below.

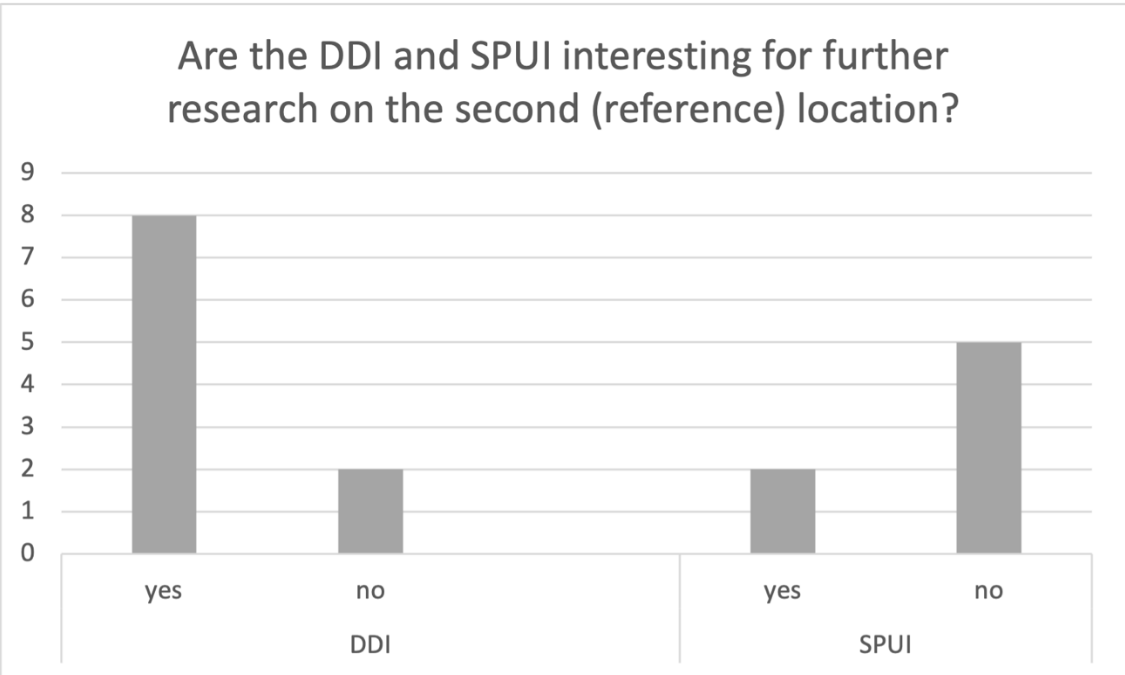


Figure 88 Results question 6 (and 7): Are the DDI and SPUI interesting for further research on the second (reference) location?

In case of the DDI, the majority answers “yes” as well. The people who voted “no”, argued that the design itself is fine, but not on this specifically location. The DDI is beneficial in situations where a lot of left-turning vehicles are present. This is not the case in this situation.

For the SPUI, the majority answered “no”. For the same reasons as the DDI, it was mentioned that the design itself is fine. The compactness of the design and the improved traffic flow are the main reasons for this. However, also in this case the location is not suitable. The SPUI is also beneficial in cases where many left-turning vehicles are present.

Therefore, it was recommended to either increase the left-turning traffic volumes, or build new traffic models for a new location where much left-turning traffic is present. This would be the N242-N508.

What chances and potential do you see on provincial roads?

Based on the presented innovative designs for intersections and interchanges, it was asked what chances and potential they see on provincial roads. The results are shown below.

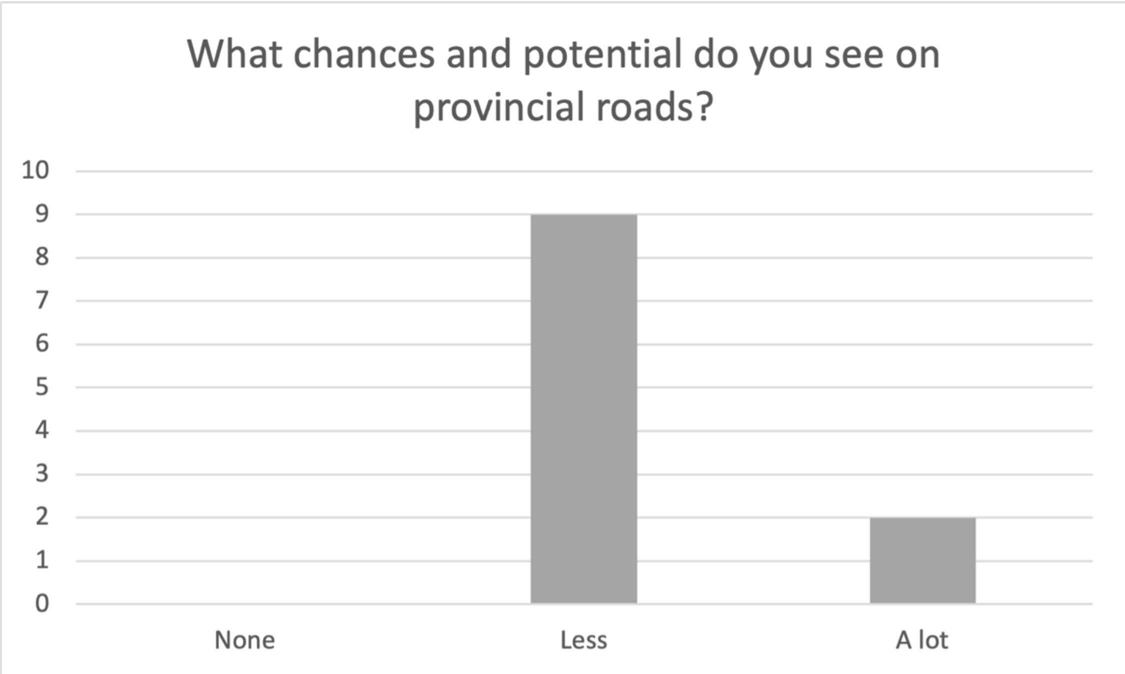


Figure 89 Results question 8: What chances and potential do you see on provincial roads?

Due to the increase of urbanization, they do have a positive attitude towards building these designs in and near urban areas, where there is a lack of space. Additionally, an important statement was made because they did not answer “less” in a negative way. It was said that customization is important, meaning that these designs might not have many use cases in the province, however, on locations where these designs can be built (i.e., locations with the right amount of traffic from certain driving directions), they can a large positive effect on the traffic situation. This includes, improving the traffic flow, as well as the traffic safety, while remaining a compact design.

Final remarks

Firstly, it was mentioned that the surface of the U-Turns might wear out quickly due to the movements, especially caused by heavy vehicles. Another remark that was made is that it would be interesting to find out how U-Turns would perform when these are not signalized or malfunction. Both peculiarities were not part of this research. For this reason, they are discussed through an additional, small literature study in the following section.

Literature study according to the final remarks

Asphalt deterioration at U-Turns

No specific studies could be found about asphalt deterioration at U-Turns. Provided that this study shows positive results for the MUT, it would be an interesting topic for a follow-up study.

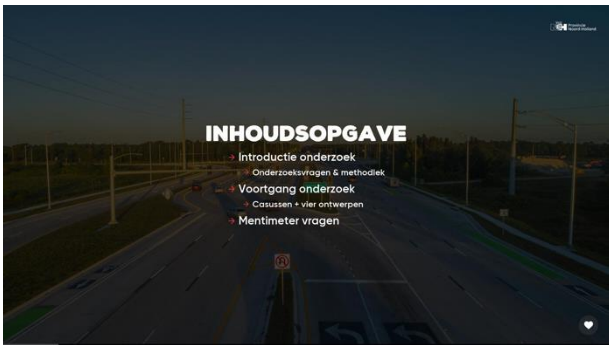
Effects of unsignalized U-Turns

Research by El Esawey & Sayed (2011) shows that the MUT, regardless of whether it is signalized or unsignalized, improves the capacity and reduces the overall delay at the intersection, compared to conventional intersections. Through simulations for a certain location, the results indicate that the conventional intersection reaches its capacity at a volume of about 1295 veh/h, while the capacity of the MUT-design with signalized and unsignalized U-turns result in a capacity of 1425 and 1400 veh/h, respectively. Expressed in percentages, this means that the capacity increases with 10% and 8%, respectively. Hence, it is shown that the difference in capacity between a signalized and unsignalized MUT show minimal differences.

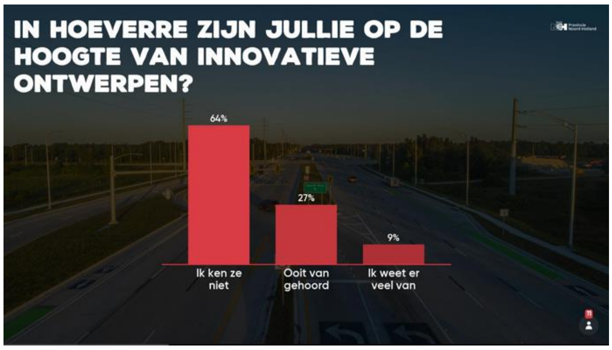
When looking at the throughput of traffic, research by Autey et al. (2012) shows that for low traffic volumes (i.e., traffic volumes up to 1100 vehicles/hour for the same number of lanes), the unsignalized MUT is the best selection over the signalized variant and the conventional intersection. On the other hand, when heavy traffic volumes are involved, it is not recommended to use an unsignalized MUT as the number of delays rapidly increase. Similarly, a study by Olarte et al. (2011) states that an unsignalized RCUT, which also has U-Turns, has an increased number of conflicts when high traffic volumes are present. In this case, the authors suggest adopting a measure to improve safety. This is by using road signs for advisory speed reductions of approximately 60 km/h.

An analysis of accident data found that accidents related to movements at unsignalized U-turns occur infrequently (Levinson et al., 2005). In urban arterial corridors, there is an average of 0.41 U-turn-plus-left-turn accidents per U-Turn per year. In rural arterial corridors, there is an average of 0.20 U-turn-plus-left-turn accidents per U-Turn per year. Based on these limited accident frequencies, the study concludes that there is no indication that unsignalized U-turns are a major safety concern.

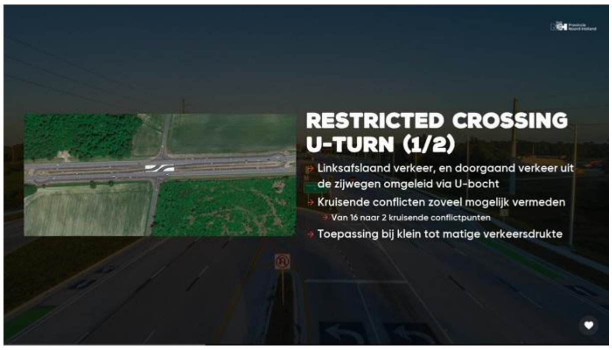
Slides workshop at the province Noord-Holland



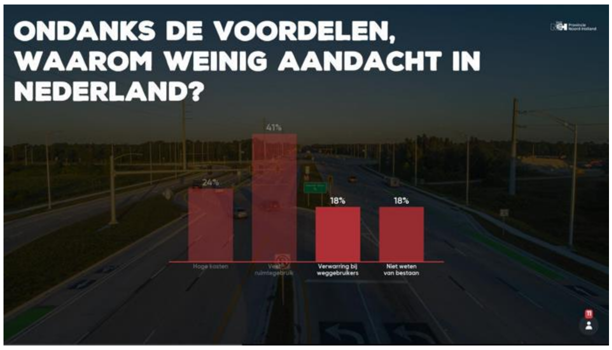

TRADITIONELE OPLOSSINGEN (2/2)
Haarlemmermeeraansluiting
Legend
= Diverging
= Merging
= Crossing
Conflict Type
Count
Crossing
6
Merging
8
Diverging
8
Total:
22 Conflict


IN HOEVERRE ZIJN JULLIE OP DE HOOGTE VAN INNOVATIEVE ONTWERPEN?
64%
27%
9%
Ik ken ze niet
Ooit van gehoord
Ik weet er veel van


INNOVATIEVE ONTWERPEN
Linksafslaand verkeer wordt omgeleid
Minder conflictpunten
Minder fasen VRI's


RESTRICTED CROSSING U-TURN (1/2)
Linksafslaand verkeer, en doorgaand verkeer uit de zijwegen omgeleid via U-bocht
Kruisende conflicten zoveel mogelijk vermeden
Van 16 naar 2 kruisende conflictpunten
Toepassing bij klein tot matige verkeersdrukte

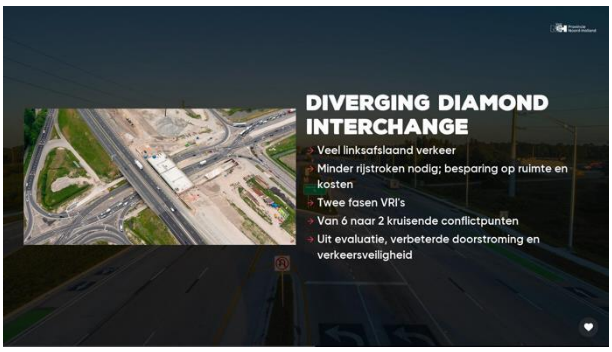

ECHELON (2/2)
Eén rijrichting van een rijbaan is verhoogd
Kruisende conflicten worden verminderd
Van 16 naar 6 kruisende conflictpunten
Toepassing bij grote verkeersdrukte

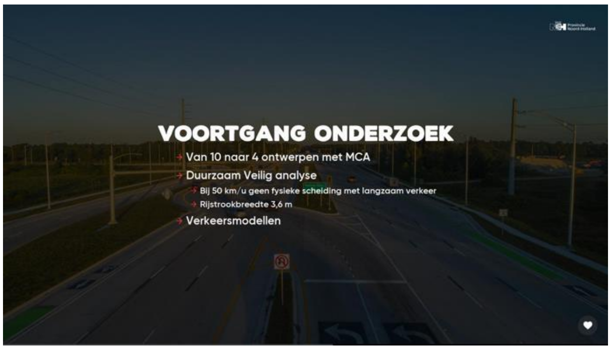

ONDANKS DE VOORDELEN, WAAROM WEINIG AANDACHT IN NEDERLAND?
41%
24%
18%
18%
Hoge kosten
Verwarring bij weggebruikers
Niet weten van bestaan


ONDANKS DE VOORDELEN, WAAROM WEINIG AANDACHT IN NEDERLAND?
Uit Amerikaans onderzoek blijkt:
Verwarring bij weggebruikers
Angst voor het onbekende
Maar:
Educatie als aanpak
Publieke opinie verbetert wanneer ontwerpen zijn gebouwd en ervaren


EERSTE AMERIKAANSE AANSLUITING IN NEDERLAND
Dit is een tijdelijk Diverging Diamond Interchange en is aangelegd om de verbinding Leiden-West bereikbaar te houden tijdens de wegwerkzaamheden aan de RijnlandRoute.


WAAROM IS SPECIFIEK DIT ONTWERP OVERWOGEN?
31%
15%
8%
15%
31%
Veel linksafslaand verkeer
Veel doorgaand verkeer
Relatief goedkoper
Snelle bouwtijd
Alle antwoorden correct

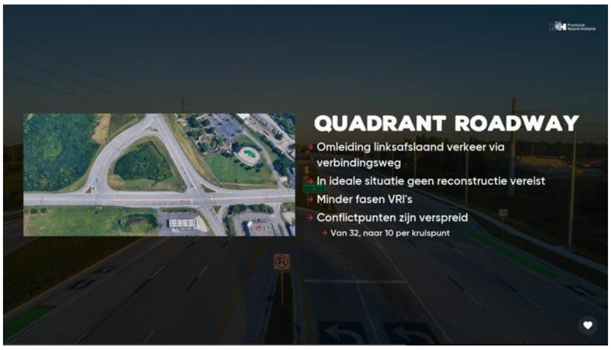

DIVERGING DIAMOND INTERCHANGE
Veel linksafslaand verkeer
Minder rijstroken nodig; besparing op ruimte en kosten
Twee fasen VRI's
Van 6 naar 2 kruisende conflictpunten
Uit evaluatie, verbeterde doorstroming en verkeersveiligheid

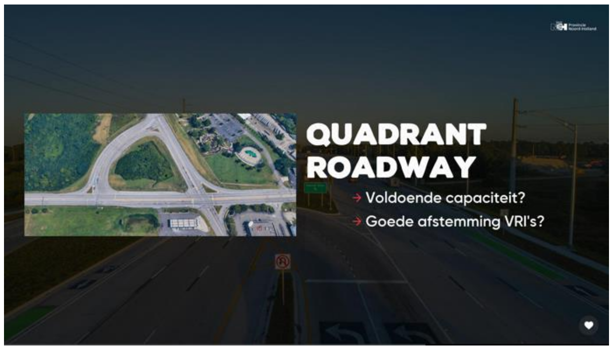

VOORTGANG ONDERZOEK
Van 10 naar 4 ontwerpen met MCA
Duurzaam Veilig analyse
Bij 50 km/u geen fysieke scheiding met langzaam verkeer
Rijstrookbreedte 3,6 m
Verkeersmodellen


4 ONTWERPEN
Toetsing onder Nederlandse omstandigheden
impact op doorstroming
impact op verkeersveiligheid
impact op de nabije omgeving


LOCATIE 1: N196-N231
Oude situatie
In de ochtend veel verkeer vanuit oost naar west
Aanwezigheid OV en langzaam verkeer
Google Earth


NIEUWE SITUATIE:
Fietstunnel
Aparte busbaan
Aanpassing aantal rijstroken


QUADRANT ROADWAY
Omleiding linksafslaand verkeer via verbindingsweg
In ideale situatie geen reconstructie vereist
Minder fasen VRI's
Conflictpunten zijn verspreid
Van 32, naar 10 per kruispunt

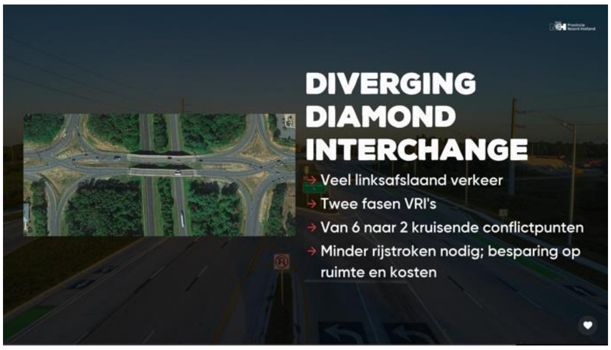

QUADRANT ROADWAY
Voldoende capaciteit?
Goede afstemming VRI's?

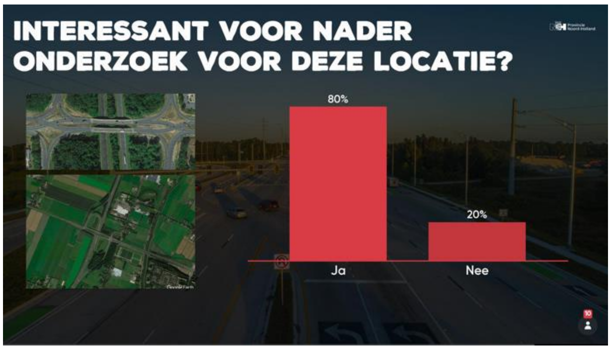

INTERESSANT VOOR NADER ONDERZOEK VOOR DEZE LOCATIE?
56%
44%
Ja
Nee


MEDIAN U-TURN
Twee fasen VRI's
Minder conflictpunten en ongevallen
Van 16 naar 8 kruisende conflictpunten
Relatief lage constructiekosten

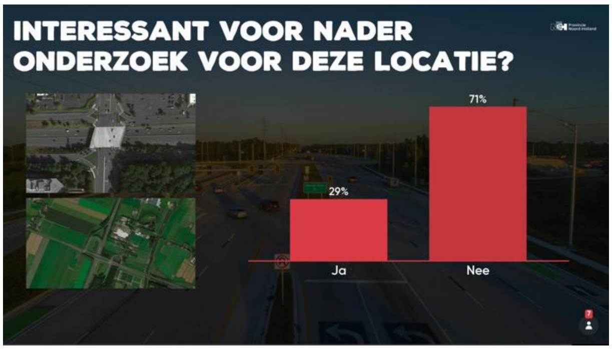

INTERESSANT VOOR NADER ONDERZOEK VOOR DEZE LOCATIE?
67%
33%
Ja
Nee

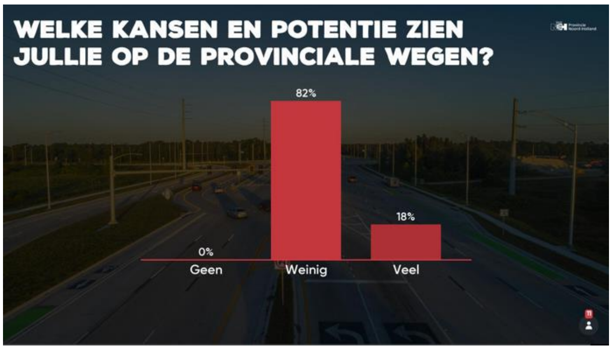

LOCATIE 2: N244-A7
In de ochtend veel verkeer vanuit het oosten
Alleen gemotoriseerd verkeer
Geen langzaam verkeer of OV
Google Earth


DIVERGING DIAMOND INTERCHANGE
Veel linksafslaand verkeer
Twee fasen VRI's
Van 6 naar 2 kruisende conflictpunten
Minder rijstroken nodig; besparing op ruimte en kosten


INTERESSANT VOOR NADER ONDERZOEK VOOR DEZE LOCATIE?
80%
20%
Ja
Nee


SINGLE-POINT URBAN INTERCHANGE
Veel linksafslaand verkeer
Slechts één kruispunt
Verbeterde doorstroming
Verbeterde verkeersveiligheid
Duur kruispuntplatform


INTERESSANT VOOR NADER ONDERZOEK VOOR DEZE LOCATIE?
71%
29%
Ja
Nee


WELKE KANSEN EN POTENTIE ZIEN JULLIE OP DE PROVINCIALE WEGEN?
82%
18%
0%
Geen
Weinig
Veel


HOE VERDER?
Informatie verwerken in eindrapport
Eindresultaten worden gedeeld
Uitnodiging voor eindpresentatie