Bicycle safety

A supersystem approach to create safety for Enschede Bike city 2020

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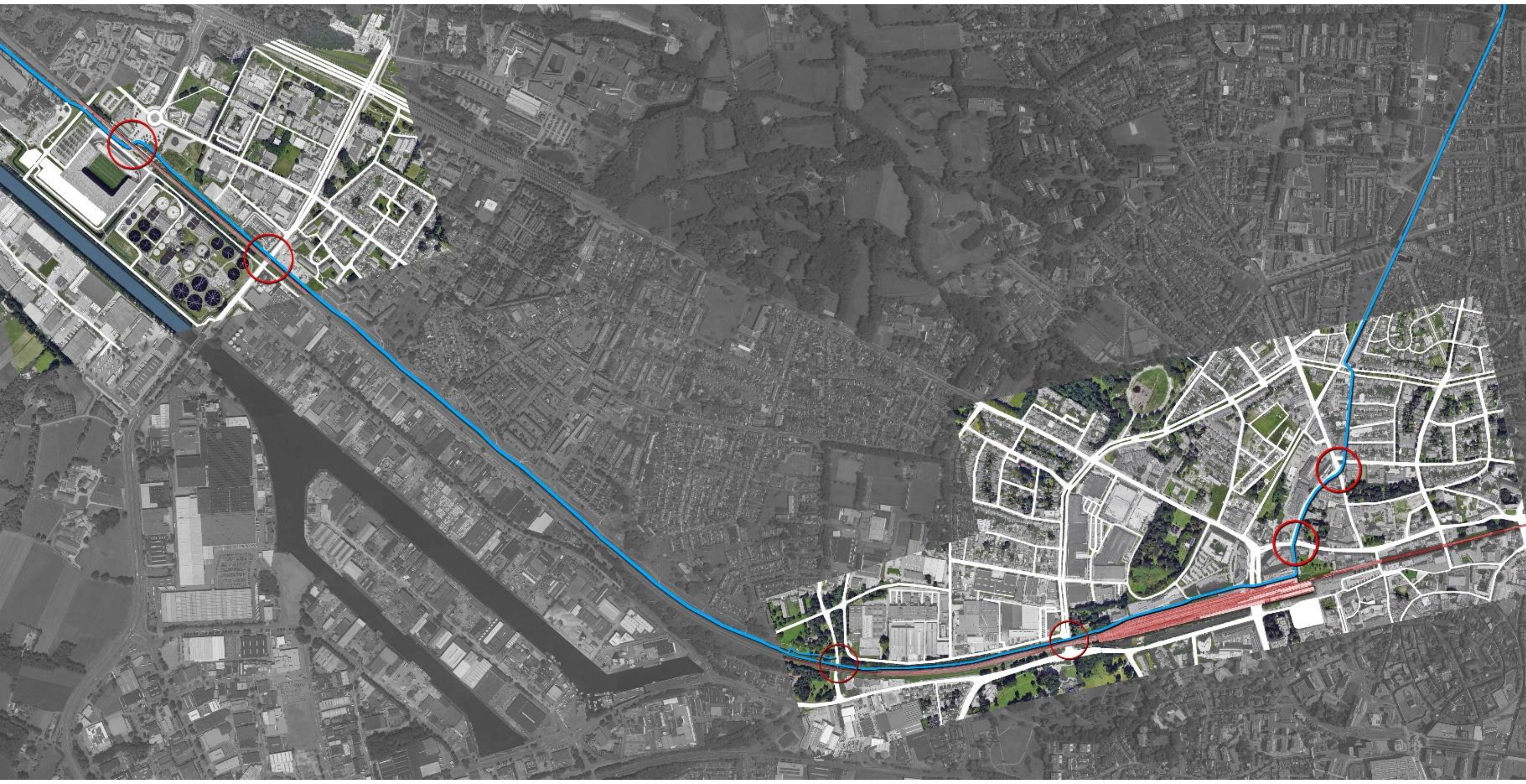

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1. Abstract

The six-step safety approach is used to identify the safety of cyclists. The system is defined using a safety cube, which discovers potential hazards that can cause failure. This lead to a supersystem approach for the remainder of the six steps. Literature research into potential hazards is used to fill in the FTA and FMEA for the most hazardous situations. These situations are controlled and monitored. To prove sufficient safety a dynamic design philosophy is created that is used to test choices of Enschede Bike city 2020. The case studies are the applications of the design philosophy. In the end it can be concluded that it is possible to structurally design the infrastructure for safety.

2. Introduction

Problem definition

On Friday the 6th of December at the intersection between the Hengelosestraat and the Raiffeissenstraat in Enschede two different accidents happen, first between two cars and later between a car and a scooter. Luckily no physical harm was done.

Normally two accidents at one location the same day might be curious but not newsworthy. However, what's special about these accidents is that they happened just after the new and improved intersection between the Hengelosestraat and Raiffeissenstraat was opened. The street had been under construction for months to get a road that would improve the safety and flow of traffic users. In particular for cyclists who came from the F35 biking highway and are on their way in the direction of Oldenzaal. The accidents on the day of the opening however did not immediately prove the improved safety that was expected (1).

The cause of this accident was said to be due to the fact that road users were familiar with the streets. Therefore they were not used to the new situation. In the previous situation the cars from the Hengelosestraat would have priority from the other streets while in the new situation they have to lend right of way to other road users. Even though this is a logical explanation, new traffic situations shouldn't be unclear when introduced. Unfortunately, these are not the only accidents that happened in the last few years in Enschede. According to a research of RTL News Enschede has the most unsafe intersections. From the top 30 least safe intersections, eight of them come from Enschede (2).

Enschede tries to improve these unsafe situations and is doing different projects to optimize the safety combined as 'Enschede fietsstad 2020' (3). The projects differ improved traffic lights that try to keep the mobile phone of bicycles users in their pocket or completely improved intersections. The F35, for example, is already a great solution. However there are still a lot of hazardous and unsafe parts that could use improvement.

Since cycling is a very important mode of transport in the Netherlands, it is vital to maintain safety of cyclists. With increasing urbanization of the global population, the Netherlands must invest and innovate to support cycling as mobility in the future landscape. Enschede acknowledges this. It is however of great importance that thorough analysis is done into the mechanisms that influence cycling safety. This knowledge can later be applied to Enschede, to help improve the cycling safety and reach the goals of 'Fietsstad 2020'.

Current trends and future expectations

In no country in the world, cycling is as important to its inhabitants as the Netherlands. With the largest distance travelled by bike per capita, Dutch cycling culture is recognized far beyond its borders. Cycling is a sustainable way of traveling and a great exercise, with all positive effects on health. The effectiveness of bike transportation is however subject to the infrastructure. Investing in bike priority lanes ('fietsstraten') and cycling highways ('fietssnelwegen') like the F35, will support the important role of cycling in the future transport scenarios.

An example of cycling infrastructure is the F35, a biking highway between Enschede and Hengelo. It seems to be a good solution for bike safety; it keeps cyclists out of the busy street with larger motor vehicles and creates a street where cyclists are only among vehicles with the same size and nearly the same speed. Such that collisions can only happen between vehicles of the same size. However, the things that are problematic are the places where the F35 crosses other with roads or public squares, for example at the Grolsch Veste. Cyclists with a high speed all of a sudden are among a tunnel with an unclear view where a lot of pedestrians are walking.

At this moment the F35 suddenly stops at the Lambertus Buddestraat, creating a situation where cyclists need to brake quickly for upcoming, and faster motorized, traffic. After that, the logical route is relatively small compared to the F35 and crosses a lot more intersections with cars, creating even more hazardous situations. At this moment Enschede tries to lengthen the F35 and also tries to avoid intersections with cars.

It is therefore valid to conclude that investment in cycling infrastructure should be widespread. Only if the infrastructure is able to nearly completely sustain the urban transport of cyclists, a safe and quick route can be offered. It is therefore crucial to be able to identify unsafe situations before accidents occur and also have insight in how to design for safety, by making the cycling infrastructure inherently safe. This maximises the ease of use for all road users, without them even knowing of the built-in safety features.

Another challenge are the increasing amount of electrical bikers today. They can go a lot faster than regular bikes, with speed pedelecs reaching speeds as high as 45 km/h. At some locations these are allowed onto the cycling highways and other parts of the cycling infrastructure. This brings the risk of creating more heavy collisions because regular cyclists don't expect the quick traveling e-bikes.

Conclusion based research question

This report focuses on enhancing the safety of cyclists by designing infrastructure for safety. Based on data analysis, literature review and safety process hazard analysis crucial hazards and safety features will be included in a design philosophy. This will in a later stage be applied to Enschede with respect to 'Enschede Fietssstad 2020'. We will look into what the potential hazards are nowadays in cycling transportation and try to find a way of improving the safety effectively. The different solutions by Enschede municipality are taken into account and evaluated whether they are safe. In this report the focus is on the infrastructural improvements rather than improving the safety design of the bike. When necessary the trade-off between safety, costs and traffic flow is taken into consideration.

Therefore, our research question is:

'How to systematically improve the safety of cyclists in Enschede by changing the infrastructural design of biking routes'.

Method explain structure

The method that is used in this report is based on the six-step safety approach given in the lectures of Safety by Design. With this approach at first the System of Interest is found. After that the potential hazards from the situation are obtained with different methods and approaches. Later these different hazards are looked further into and how these could be improved upon. Finally we try to create a conclusion and philosophy how to improve the structure This is put into practise with case studies taken from the plans of Enschede city to become Bike City 2020.

3. Define the system

Explanation Safety cube

In most of the design processes safety is rather seen as a requirement instead of a prerequisite. In this case designers look for failures from the design and how to optimize this so that an unsafe situation is avoided. However not only the product can fail but also the system in which it interacts. If a product works perfectly fine but the system is behaving differently than expected, than unsafe situations can still exist. To implement safety earlier in the design process the safety cube is created. The Safety Cube looks more into the system at different levels and in different time scheme's to see how the system can fail. The time is divided into three different 'periods'; the past, the present and the future. With this approach you can see how comparable systems have worked before and expect how in the future the system will change because of new trends. From top to bottom you work with the level of systems, starting from super system (which is the environment in which it interacts), the system itself (also called System of Interest, or SoI) and at last there is the sub-system (parts that create the system).

The safety cube has also three sides (resulting into 27 different squares) which all represent a part of a system that can make the product or the system fail itself. The three sides are Operational (people), Structural (system) and Functional (environment). The operational view translates how people would (mis)use the system, the structural level translates how the physical structure interacts and how this might fail and lastly the functional view goes into depth what functions a system should perform and how this could fail.

Explanation systems

To perform a Safety Cube analysis it is important to get a grasp of the System of interest, what it's components are (sub-system) and in what environment it behaves (the super-system). In this report the safety of cyclists is taken into consideration especially in Enschede where the cycling-highway (F35) should optimize the safety of cyclists in the city. Although the F35 is fairly safe there are a lot of intersections and a lot of places where cyclists can not use the f35. Thus the cyclists is acting in a larger system consisting of the F35 and other roads. This super system has some parts which interacts with the user again which can be seen as the sub-system. All the three systems are stated below. Also a summary of what elements are included in each part are given.

Super-system

The super-system is the complete infrastructure of the city Enschede that is necessary for cyclists to get from one point in the city to the other. When used as intended the cyclists will mostly use the F35 as the larger part of its route. However the F35 is not everywhere in the city which means that cyclists will leave the F35 and cross multiple intersections which are shared by different types of vehicles such as pedestrians, cars, trucks, etc.

Stakeholders: *Roads, road signs, intersections, biking lanes, biking streets, biking highways, lampposts, traffic light, line indication, central reservation.*

System of interest

The user combined with his/her bicycle is considered as the System (of Interest). He/she will move around within the super-system to get from one point to the other and will cross multiple roads and intersections. The user will need to pay attention to get a grasp from his/her surroundings to find out if it's safe enough to cross the road. With the information the cyclists needs to operate according to the given information.

Stakeholders: *Cyclists, E-bike bikers, scooter-users, car drivers, pedestrians, police officers, speed pedelecs, truck drivers.*

Sub-system

The sub-system consists of all the parts that make up the bicycle that the operator is using. For the safety cube only the parts are taken into consideration that could create an unsafe situation while operating in the super-system, such as the lights (cyclists cannot be seen) or the brakes (cyclists cannot slow down before an intersection).

Stakeholders: *Brakes, Lights, Gears, Bell, bicycle stand.*

Time periods Safety cube

To create safety in the use of a product it is important to learn from previous mistakes (made by others) but also look into the future what can change over time which results into dangerous situations which are not present in the use scenario today. It is important to note how the environment used to be in the past, how it is today and how it will probably look like in the future. These three periods are given below.

Past

The city has roads which are all shared by different type of vehicles (trucks, busses, cars, cyclists etc.) with the exception of highways. Some roads may have different segments for different road users so that these vehicles have their own lane, however they can still have contact with each other.

When it comes to vehicles there are mostly no e-bikes.

Present

The roads are more and more divided into separate roads for different type of vehicles to create safety and an optimized traffic flow. The cycling paths are separated from the streets and if this is the case cyclists are prohibited to use the road meant for cars. The cyclists also have their own biking highway so that cyclists do not cross their paths with other -bigger- road users such as trucks and cars. However the cycling highway consists of segments meaning that there are a lot of - unsafe - intersections with regular roads.

When it comes to vehicles there are more e-bikes (400.000 new e-bikes where sold in 2018 (4) which on average can go faster than regular bikes. Then there are also speed pedelecs which can go up to 45 km/h. Since the biking highway is mostly meant for bikes the highway invites all the different types of cyclists to go as fast as they can. This now means that you have slow regular cyclists combined with bikes that can go 45 km/h and also motorized scooter which also go faster. This can create unsafe situations because now cyclists need to anticipate on each other.

Future

In an optimal future situation there are even more roads meant for one type of vehicle. So cars use a separate road and bikes do as well. The biggest danger - intersections - have been replaced with overhead bridges so bikes can cross the road without having to come in contact with cars (however there still might be some intersections). Since speed pedelecs and e bikes go way faster than regular bikes there are different segments on the biking highway so that both will not intervene with one another.

Safety cubes

With all the information combined the potential hazards are obtained in the three different hazard categories (Physical hazard, Functional Hazard and Operational Hazard) . The hazards were found by using the above information, research and brainstorm sessions. The hazards are placed in the right time segment and the right layer of the system. However some hazards can be placed in more time segments and it might not always be clear in which layer of the system it fits(5).

Physical Hazard assessment

	Past	**Present**	**Future**
Super system	Small vehicles have to share the same road with vehicles like cars and trucks which do not match the same speed. Bad pavement creating broken roads. Bad line indication meaning that road users do not know where to/where to stop putting them in places where they should not be. Bad weather creating icy roads which causes road users to slip and don't have control over their vehicle.	Busy intersections so road users can not cross the road which can lead to the users making their own -dangerous- decisions Bad vision of what is coming from different sides which leads to road users making decisions which can be dangerous No room to stand still putting the road users on places where they should not stand. Needing to brake on a slope, if a cyclists has speed it might be difficult to brake on a slope	Busy roads that need to be shared with similar vehicles that go faster, this means that if a cyclists make swing it can crash into another cyclist. No room to overtake other cyclists so fast cyclist come very close to slower vehicles No room to step aside, if something's wrong with the bike you need a place to check/repair this, however standing still on a road with fast cyclists can be dangerous because their brake-path is slower.
System	Vehicle breaking unexpectedly in front of the cyclists which mean they need to brake quickly as well. Bicycles being relatively small which mean that they are not so good to be seen by larger vehicles such as trucks Vehicle unexpectedly turning left or right without using an indicator, which means cyclists cannot anticipate	Vehicle blocking the bike lane, it is easy to park a car there Being in the dead spot of a truck, since cyclists are relatively small he/she can be in the dead spot.	Slower vehicles are unexpectedly swinging on the road which means that they can bump into an overtaking cyclist Vehicles blocking the way out of the biking highway if they are standing still on an exit.
Sub-system	No proper lighting meaning that they are badly visible for other road users	No proper lighting meaning that they are badly visible for other road users. No proper brakes so they will not brake in time for an intersection Dead battery on e-bike so that they will suddenly stand still	Dead battery on e-bike so that they will suddenly stand still Failing cruise-control meaning that they will cycle faster than allowed on certain segments No prober lighting meaning that they are badly visible for other road users No prober brakes so they will not brake in time for an intersection

Functional hazard assessment

	Past	Present	Future
Super system	Bad weather creating failing parts such as frozen braking cables Failing stoplights meaning that it's unclear who goes first on an intersection	Bad weather creating failing parts such as frozen braking cables or batteries on an electric bike Failing stoplights meaning that it's unclear who goes first on an intersection	Bad weather creating failing parts such as frozen braking cables or batteries on an electric bike
System	Having too much weight on a bicycle meaning that it more difficult to brake in time	Vehicles don't show where they're going creating unclear situation if cyclist can overtake the vehicle or not	Vehicles don't show where they're going creating unclear situation if cyclist can overtake the vehicle
Sub system	No proper lighting meaning that they are badly visible for other road users No proper brakes so they will not brake in time for an intersection Worn out tires	No proper brakes so they will not brake in time for an intersection No proper lighting meaning that they are badly visible for other road users Brakes are not powerful enough Worn out tires Gears are stuck which means that the cyclist cannot accelerate quick enough from a full stop and thus will need longer to cross an intersection	Automatic braking failing Worn out tires

Operational hazard assessment

	Past	Present	Future
Super system	Bad weather blocks view for road users creating a dangerous situation where other road users are not seen Surrounding make it difficult for the driver to pay attention, this can be distracting street signs or other information No proper signs which can lead to road users making wrong decisions	Bad weather blocks view for road users creating a dangerous situation where other road users are not seen Surroundings make it difficult for the driver to pay attention, this can be distracting street signs or other information Unclear who is in the priority lane and has priority in the intersection Unclear if you're allowed to overtake, some streets are not made for that but can look like they are	Bad weather blocks view for road users creating a dangerous situation where other road users are not seen The road does not give a heads up for an intersection and thus cyclists are not expecting it, meaning that all of a sudden they have to decide quickly what to do Vehicles are not ringing meaning that they don't notify other users that they are overtaking them. Vehicles are not ringing meaning that they don't notify other users that they are overtaking them.
System	Cyclist is looking on his/her phone and getting distracted from the traffic Cyclist gets distracted by other road users and is not paying attention to anything else Cyclist going into a non-entry street creating a situation where they should not be	Cyclist gets distracted by other road users and is not paying attention to anything else Cyclist going into a non-entry street creating a situation where they should not be	Cyclist gets distracted by other road users and is not paying attention to anything else Cyclists gets distracted by bike computer and is not paying attention to anything else
Sub system	Cyclists don't break in time creating a possible collision between different road users Cyclists forgets to turn on lighting meaning that they are not visible for other road users	Cyclist forget to turn on lighting meaning that they are not visible for other road users	Cyclists don't set the settings of the e-bike to the proper setting meaning that they go to hard on roads

Conclusion

Although in all the three views a lot of hazards can be found, it can be seen that they are mostly not due because of system or subsystem failure. It's rather the environment creating unsafe situations or situations in which the cyclists make bad decisions. If the infrastructure is not inherently safe, the cyclist could make the situation dangerous themselves. In that case it would be smart to create a better environment to take away those specific dangers.

4. Define safety objectives

Accidents related to the Netherlands

The create an idea about numbers of incidents in the Netherlands within traffic, the Dutch Central Bureau of Statistics (CBS) collects these numbers and publishes these numbers to in a summarized document each year. These numbers of the past 20 years have been collected and can be examined online in a tool the CBS developed (6). Relatively, the share of fatal cycling accident has increased from 19.1% to 33.6% over the past 20 years. In numbers, this means a decrease of 239 accidents to 228 accidents. This relative increment of percentage is mainly because the car industry has been improving in safety a lot. The fatal accidents in numbers for cars have decreased by 400 occurrences. It is important to note that the total share of accidents has decreased from 1251 to 678 occurrences. If the total safety of mobility can be increased in such large numbers, it should also be possible to make bike safety improve in numbers.

For bike safety, a couple of important indicators play a role in order to increase the safety level. First of all the amount of travelled kilometres by bike per person in the Netherlands stayed around the same number. This is roughly 800 kilometres per person per year. The second indicator is the number of users of a bike. This number has increased over the years, this makes the use of bikes in fatality numbers per travelled kilometres safer than 30 years ago (7). The fatality rate when cycling has been going down by 67%, this number is much more correlated to the improvement in the car industry described in the first segment of this chapter.

Overall the trend of mobile safety is moving forward in a positive motion, The risk of a fatal accident has decreased per kilometres cycled or driven. However, the number of accidents in bike mobility has not decreased. When looking to these numbers, an interesting trend can be found that is connected to age. The older groups, older than 49 years, actually have an increased risk of a fatal accident over de last 20 years. This increase in risk is around a relative increase of fatality of 21%. Since 2014, an increased number of fatal accidents occurred with E-bikes. This number almost grew exponentially within the last 5 years. This number expanded from 16 accidents in 2014 to 57 accidents in 2017 (8). In the future measures have to be taken to improve safety for this target group especially since it is the only group that is significantly increasing in fatal accidents.

Accidents related to Enschede

With the opening of the new Raffeisenstraat to the Hengelosestraat, immediately 2 accidents happened that day. The reason for these accidents is that the priority rules for the intersection changed to the situation it was before. The accidents mainly happened because of the negligence of the drivers on this road (9).

Cyclist are relatively vulnerable traffic users. This mobility group is using the same road as for example cars, which are relatively safe compared to bikes. Combining 2 groups on the same road with different levels of vulnerability is always dangerous. Most accidents that end fatally for bike users happen on intersections or at least within the city limits. These are places where traffic is concentrated and the likelihood of an accident occurring is higher (10).

Looking to intersections in Enschede, it is remarkable that Enschede has such a low rating on different intersections. 8 of 30 worst intersections in the Netherlands are located in Enschede. These intersections are called "black spots", this means that in the past 3 years, more than 10 accidents have occurred (2). Enschede is planning to do something about this. This requires a cause to this high occurrence rate and this is still guesswork. This report should help to locate different hazards that lead to these accidents. By eliminating these hazards, the probability of occurrence will decline.

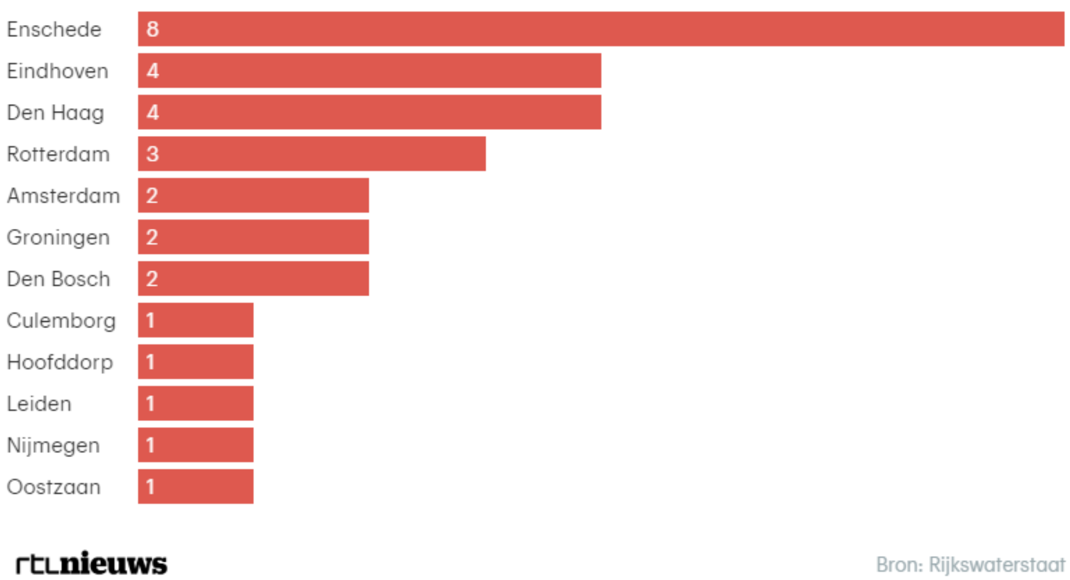


Figure 1: RTL Number of black spot intersections over different Cities.

Current legislations

From the safety cube analysis it is found that the system of interest has connections to infrastructure and to parts of the system that ensure safety. In this part of the report, a list will be made that directs to certain regulations of the European and Dutch regulations. These regulations will also contribute to either the sub-system safety or the overall safety. This implies that the safety of the system of interest will also improve.

In the Netherlands, 2 different documents on safety are found. The 'Wegenverkeerswet 1994' (11) and the 'Road traffic signs and regulations in the Netherlands 1990' (12).

The Wegenverkeerswet 1994 regulates what speed certain vehicles can travel and what restriction on power these vehicles have. The Road traffic signs and regulations in the Netherlands 1990 adds that helmets have to be worn by the drivers of certain vehicles.

The Wegenverkeerswet 1994:

- Electric bikes that go up to 25 km/h, have a maximum of 0.25 kW and the power should gradually go down when reaching the 25 km/h limit.
- Scooter or other motorized vehicles with 2 wheels can go up to 45 km/h, with a maximum cylinder volume of 50 cc. The power limit is 4 kW.
- The minimum age is sixteen, the only exception is an electric bike that is classified as a normal bike.
- For motorized vehicles up to 45 km/h a drivers license in required.
- These regulations apply if the vehicle is used by a non-disabled persons.
- When a vehicle has a speed limit of maximum 25 km/h, a cylinder volume of maximum 50 cc and motor power of less than 4 kW, the vehicle can be accepted by the minister without permission of the European Union.

The Road traffic signs and regulations in the Netherlands 1990:

- Cyclists are allowed to drive with 2 next to each other, Riders or motor-assisted bicycles are not allowed.
- Cyclists are required to use the mandatory cycle tracks or cycle/motorcycle tracks.
- Bicycles having more than 2 wheels or have a width exceeding 0.75m, may use the public carriageway.
- Motorcyclists are required to use the mandatory cycle/motorcycle tracks.
- Lights are mandatory. White front light and red back light.
- Lights are mandatory when vision is impaired in any situation (night, mist, fog, etc.)
- Helmets are obligated in motorised vehicles that have an open compartment.
- Helmets are not required to be worn by motor-assisted bicycles.

The European norm sets requirements for each state of the European Union. This requirement is the same for all nations currently in the EU. However, there is a huge difference in the appliance of different rules between different countries. This is possible since every nation can act differently on certain parts of the law. There are regulations that need to be met, but there are also directives or decisions that are much more freely to interpret.

This means that every nation acts differently to certain safety measurements. Therefore, the most important measures should be found in the documents the national government provides. However, all products or systems that are applied should be made according to these European standards. Therefore, research into these documents concluded the following. For each type of product like a bike or electrical vehicle are loads of documents describing how such a product should be made. Not all of these documents are necessary to follow if they are not prescribed as an obligation according to the law. It is important to find out which of these documents are obligated.

For bikes the ISO 4210 about safety requirements for bicycles is important. Next to this document, legislation for tyres and rims, for lighting and reflection, for luggage carriers and lastly for bike chains can be found. These links can be found in the ISO 4210 as well.

For electrical powered bicycles even more documents can be found that are investigating the safety of the batteries and motors. This also describes how these parts should be covered and a lot more regulations on transport and the electrical parts. One of the most important documents for these regulations is the NEN-EN 15194:2017 which is about electrical powered bicycles. This document can direct to other parts described above.

The European Union sets up documents to guarantee safety of the products in Europe. The complexity of these documents is high because there are simply a lot of documents. Due to the scope of the project, it is decided that the Dutch regulations are enough to create a sound Fault tree analysis.

Future safety objectives

In the future, bike safety will change because new vehicles will be introduced. With the introduction of the e-bike, electrical scooters and other almost silent high-speed bike lane users, safety changes. From research, it is found that the car industry went through big changes that increased safety by large amounts. One of the safety objectives is to improve the safety for bikes as well. Focus on bike infrastructure is a very important aspect. At this moment bikes are generalised into one big stack, while for the future it might be necessary to split this stack.

When this stack is split, it can be more easy to distinguish normal bikes from motor-assisted bicycles. Since these bicycles are more and more used, the safety objectives of these bike should be reassessed. The difference in speed on the bike lane will be a thing to look into.

Within this report, the method will give an overview of the current situation and the methods used will indicate what the most dangerous situations are right now. These situations can be compared to future expectations and then a future strategy can be developed. This strategy should be the design philosophy for future bike projects.

A last safety objective that needs to be addressed is the shifting mobility mindset. Mobility by ownership is changing to mobility by access. People are buying new cars that will drive automatically, if these products are designed properly, the human error of driving will be lowered. This mainly contributes to the safety of the users of cars, but it also contributes to less multiple vehicle accidents, in which bicycles can be contributing. If all cars are driving automatically the safety of bikes is in that way improved as well. There might even be a way to design a bicycle vehicle that can drive in a similar manner. However, in this report the focus will be on infrastructural improvements of the bike lanes and crossings with car roads.

5. Identify Hazards

To map and identify safety hazards and incidents, a systematic approach should be applied. Safety process hazard analysis (PHA) is a procedure that is used to map or to improve upon safety. There are numerous methods available. These have specific applications and each of the tools sheds light on a specific aspect of safety.

Fault Tree Analysis

A very useful form of PHA is the fault tree analysis (FTA). This is a visual mapping scheme that helps to deduce the source of a collision, based on lower level events. These schemes can be constructed either bottom-up or top-down. Depending on the situation it might be more favourable to investigate the root causes of a known failure mode, while in other cases FTA is used to investigate the possible outcomes of existing hazards. An important property of FTA is the fact that it is based on logic, which means that the schemes are built up using logic operators such as “and” or “or”. By using the logic operators it is possible to formulate a conditional scheme, that can be used to model the failure. For this, it is imperative to also gather statistical data or estimate probability such that the chance of collision can be determined. By using axioms of probability, various formulations can be created to determine or estimate the probability of the top level failure occurring based on the chance of occurrence of low level events.

In case of cycling safety, the sub events in the FTA can be hazards related to traffic safety. Hazards such as unsafe road conditions, distracted drivers or cyclists, intersections with poor overview, infrastructure without build in safety features, unclear marking or signage, etcetera could all contribute to the occurrence of a collision. As stated before, logic is used to connect the hazards to higher level events. It is therefore important to have insight into the interrelations of hazards. For instance, the relation between the simultaneous occurrence of slippery road surface and a distracted cyclist that is using a mobile phone and its effect on risk of collision.

There are some situations where the fault tree depends on the same event for different effects in the model. This is denoted as a common cause model. Mathematically this introduces a challenge as the system is no longer independent and top-down. The dependency issue caused by common cause can be overcome in certain simulation environments. However, FTA is also a great tool to obtain insight in the causality of failure modes, even without having to model and simulate the system. The graphical overview that is obtained using FTA is a great way of getting a substantiated feeling for the mechanisms behind the hazards of the system at hand. After using the FTA to identify and map the hazards, FMEA will be used to offer more insight into the mechanisms behind the failure modes. To this end, two high risk failure modes will be used to construct a fault tree analysis.

Failure Mode and Effects Analysis

A good follow-up PHA is the method known as Failure Mode and Effects Analysis (FMEA). This tool is not necessary used to map hazards, but mainly to determine the possible effects of these hazards which are identified. The effects can be classified using the severity and the probability of a certain hazard. Causes of failures and the modes of failure can also be brought into the analysis. Typically this form of analysis yields a large table including nearly all possible modes of failure. These tables can be based on expected or simulated modes of failure. Statistical models can be used to evaluate the probability of the hazards that have historically occurred. The latter variant only includes highly probable forms of failure, which more often come at a low severity. If we are interested in the modes of high severity and very low probability, it might become hard to base the failure mode on historical events, because those hazards are unacceptable to occur in the first place. In this case the risk is estimated by using the product of severity and probability. The outcome can then be used in the design phase to create an overview with all high risk hazards, such that the most important and impactful can be partly or completely mitigated during the design phase.

Both the severity and probability can be determined using an (expert) rating on a scale. There are versions of FMEA available that give a guideline description for every rating, adapted for a specific industry. Risk can be converted to risk priority using the detection rate, which is also a score on the scale. High detection rates ensure that even though the hazard exist, there is only a small chance of it leading to failure, because it can be easily detected before the accident occurs. This is considered a well-controlled hazard. The risk priority number (RPN) is then calculated as the product of severity, probability and detectability. FMEA will be applied to the cycling safety in the Netherlands base on the hazards which are mapped out by the FTA. Combining these two methods of PHA, obtains well-structured and complete insight into cycling safety.

FTA result

For the FTA, most of the input is taken from an in-depth study done by VeiligheidNL (13). This study was conducted commissioned by the Dutch Ministry of Infrastructure and Environment (I&M). The analysis in this study was done based on statistics around ‘spoedeisende hulp’ first aid events. The root cause and demographic information of every incident was gathered, also by using surveys conducted under the victims of traffic accidents that resulted in first aid treatments. The survey was also conducted on the general cycling demographic, to be able to create a more general overview of root causes of incidents.

In the report, a clear distinction is made between single-vehicle accidents and multi-vehicle accidents (collisions). These two types of accidents are taken as the top level events in the fault tree analysis, namely, ‘severe bike-car collision’ and ‘cyclist crashes in single-bicycle accident’. The root causes are based on the results of the survey conducted under first aid victims and general cycling demographic. The resulting fault trees (Figure 2 and Figure 3) are quite detailed and therefore also displayed at a larger format in the *Appendix*, to maintain readability. In these diagrams, all green events are a result of behaviour of car drivers, blue are a result of behaviour of cyclist and the grey events are a result of infrastructure. Because our method is the safety by design of infrastructure, we focus our attention mostly to these events.

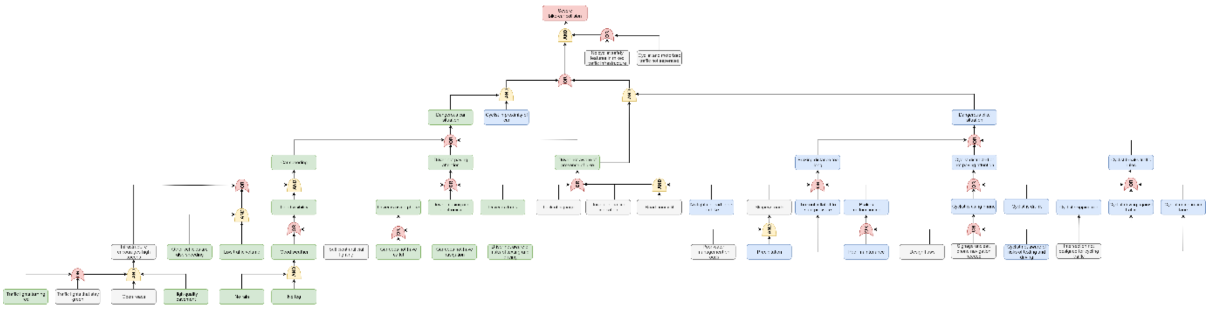


Figure 2 - Fault tree of severe bike-car collision.

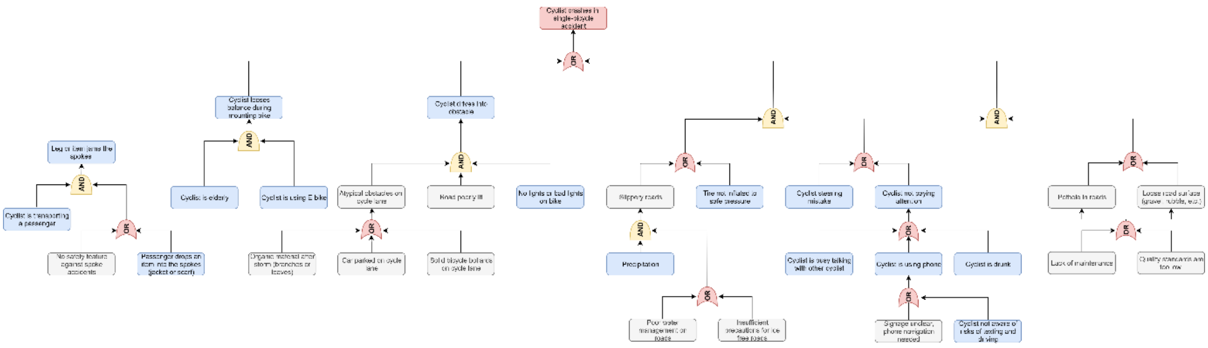


Figure 3 - Fault tree of single-bicycle accident

Contrary to the FMEA, fault tree analysis is a very valuable tool to express the logic behind the failure modes. FMEA is great at quantifying the effects of failures and their risk priority but does not entail that much detail about the mechanisms behind failure. As can be seen from the two diagrams, that the top-level failure only occurs when multiple hazardous events occur at the same time. Of course, both diagrams are condensed and do not include all possible sub events that could lead to the final failure mode. They do illustrate however that both modes of failure are very much dependent on the conditions that allow the failure to occur. Interestingly, these sub events could function as critical control point. By collecting data on the occurrence of the subevents, the total probability of the final failure can be investigated independent of the final failure mode even occurring.

A lot of these critical control points could be taken as a part of the infrastructure. Road conditions, such as potholes, icing or poor water management can be monitored and improved upon to mitigate accidents. More importantly, is the fact that most of the possible routes accidents can only occur if the infrastructure allows for those unsafe conditions to exist in the first place. A very distinct and logical example is in the FTA corresponding to the bike-car collision. If the infrastructure is design such that cycling and cars are separated, even if both the dangerous car situation and dangerous bike situations occur, a collision is not a possible result. This is a feature that makes the infrastructure inherently more safe. Dangerous intersections can be made more safe by separating cars and cycling traffic before the intersection, by implementing flyovers or separation features like concrete or natural traffic dividers.

Another important consideration is that infrastructure can be designed such that it does not allow for unsafe situations to occur, simply because the infrastructure pushes the drivers or cyclists behaviour away from hazards (Figure 4). Examples are narrow roads with high curbs, twisted into chicanes if necessary, such that car drivers will lower their speeds automatically. Clear signage and line indication support more safe behaviour without limiting the freedom of travellers with rules and supervision.

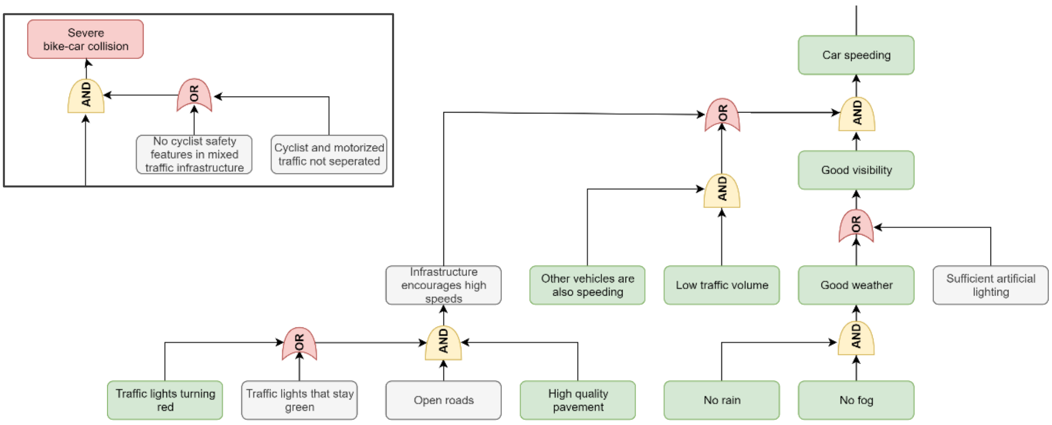


Figure 4 - Part of the bike-car collision fault tree, focussed on the infrastructural part that enables dangerous car situations. Insert is the Boolean top level of this fault tree.

There are some accidents that can be very hard to rule out via the safety by design method. Sometimes cyclist, either unexperienced, elderly or simply not paying attention will make silly mistakes (Figure 5). Because a cyclist is exposed to falling on concrete or road surface inherent to the mode of transport, these accidents are hard to control and prevent. More cycling experience has been reported to decrease the risks of these accidents in the same report. Following that line of thought, a more safe and user friendly cycling infrastructure will lead to more people using bikes and inevitably also reducing the risks of these accidents occurring.

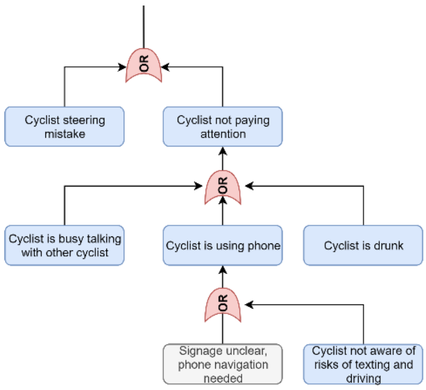


Figure 5 - Part of the single-bicycle crash fault tree. This part shows the impact of cyclist concentration or skill.

FMEA result

Based on the results of the FTA, two important hazards are taken as input for the FMEA. These two hazards are ‘slippery roads’ and ‘No cyclist safety features in mixed traffic infrastructure’ because these two hazards have a contribution to many possible modes of failure. Whenever there is a lack of statistical data or experience based knowledge, guesstimation strategies were applied to obtain a complete picture. This strategy was applied to the severity factor, probability factor and detectability factor. As a result of these factors, the risk priority number (RPN) is obtained.

The FMEA indeed shows that even hazards with a high severity don’t necessarily imply a high risk priority. Only if the probability is also high and detectability is low, the hazard has a high RPN. What is important to note is that most of the hazards that exist will only lead to failure if there are errors in the infrastructure to begin with. This means that there are plenty opportunities to overcome hazards by designing a safer infrastructure that removes the risks completely. Creating a safe situation for cyclists often means making safety independent of human errors. This can be done by separating car traffic completely from cycling traffic for instance. In some situations, this is possible and adds value to the infrastructure. An example is the F35. Due to the huge added value this road network brings for cyclists, it is justified to invest more in critical infrastructure.

Table 1 – FMEA of slippery roads as hazard.

Hazard	Potential effects of hazard	Severity	Possible cause of hazard	Probability	Current control	Detectability	RPN
Slippery roads	*Falling and getting bruises and scratches*	5	*Slippery road because of poor maintenance*	4	*Rostered maintenance and inspection*	3	60
	Falling and getting severe damage to face	7	*Hit curb/sidewalk due to poor design*	6	*Rostered maintenance, inspection and citizen reports*	3	126
	Having to slow down or stop	1	*Slippery road because of poor maintenance*	8	*Rostered maintenance and inspection*	5	40
	Riding into tree and crashing	4	*Unsafe behaviour*	5	*Biking certificate during primary school*	6	120
	Collision with a car and getting broken bones or worse	8	*Slippery road because of poor maintenance and a speeding car*	6	*Rostered maintenance, inspection and police control*	1	48

In Table 1 the FMEA of 'slippery roads' is displayed. This hazard was chosen as it leads to dangerous situations in both the bike-car collision and single-bicycle fault tree. Cars and bicycles are both dependent on the traction offered by the road surface to safely manoeuvre as traffic. It is however important to understand that this hazard can be controlled (detected) via inspection or even mitigated by regular maintenance. For this reason, almost all possible failure effects have a high detectability. Only having to stop and slow down as a cyclist, has a low detectability. This is because it simply has a low priority in maintenance. Cycling traffic should be safe in the first place. Therefore maintenance effort is not directed towards cycling speed. Otherwise, it is also important to note that the hazard 'slippery roads' doesn't independently lead to failure effects for the highest RPN's. With other words, only if other hazards co-exist with this hazard, the worst failure effects can occur.

Table 2 shows the FMEA of the hazard 'lack of cyclist safety features in mixed traffic'. As the hazard itself also describes, this hazard is only in place if there is mixed traffic in the first place. A direct solution to overcome all the effects of this hazard is to separate the cycling traffic from that of cars. This can however be costly in certain situations or simply not possible due to spatial limitations. For this reason, the option of inserting safety features for cyclist is given. With this we consider placing clear line indication or surface colouring that visually aid the cycling strip, placing barriers near intersections or roundabouts and also traffic islands. The FMEA shows the risks if these features are not in place. The highest RPN is obtained in case a cyclist is hit by a speeding car. In this case the driver is also not paying attention, the road is poorly lit and the cyclist has no proper lighting. This again a confluence of multiple hazards, on top of the hazard that was denoted as a lack of safety features. This means that even if all these hazards occur, the final failure effects could have been prevented if only the infrastructure contained enough safety features.

Table 2 - FMEA of lack of cyclist safety features in mixed traffic as hazard

Hazard	Potential effects of hazard	Severity	Possible cause of hazard	Probability	Current control	Detectability	RPN
Lack of cyclist safety features in mixed traffic infrastructure	*Bike-car collision at intersection*	6	*Driver speeding and cyclist distracted due to a lack of line indication*	3	*Solid infrastructure design, police control and regulations.*	3	54
	Death of cyclist	10	*Driver not paying attention and speeding, cyclist without lights, poorly lit roads.*	3	*Solid infrastructure design, safety awareness under cyclists, police control and regulations.*	7	210
	Car has to brake hard because cyclist comes out of unexpected direction and causes chain collision	8	*Lack of signs, cyclist without lights, cyclist unaware of risks, road poorly lit*	2	*Solid infrastructure design, safety awareness under cyclists, police control and regulations.*	8	128

6. Control Hazards

In this report the focus lays on optimizing the infrastructure of a city to improve the safety of the cyclists. According to the safety cube and the FTA it can be seen that the environment is the part of the system that is due to a lot of potential hazards. There are of course some elements that could be improved to the bike like better lightning or rusty brakes. Even if they are working according to regulations this does not guarantee the safety immediately. Taking away possible hazards from the environment can already have a lot of impact.

Every potential hazard should have a solution for it so that the hazard can be taken away and thus decrease the chance of a collision. Every potential hazard can have multiple solutions However, the most safe solutions are not always the most optimal solutions; for example, creating a completely different route for cyclists at every intersection so that they will not intersect with cars can be very safe but is too expensive to do at every intersection. That's why cost and efficiency should both be an aspect taken into account when improving the environment. Out of the FTA's for single bike accidents and bike-cars collisions the hazards that are due to the environment are being examined for solutions. The potential hazards are given below and are explained why these are hazards and how these could be improved. Also it is given what their relative prices are and if these solutions are efficient.

Intersection not designed for cycling traffic

These are intersections with no cycle lane meaning that the bicycles have to put themselves on the same lane as larger traffic such as cars and trucks. This also means that the same rules -for priority - apply to cyclists and motor vehicles alike. This could potentially be dangerous since bicycles can now be anywhere around a car or truck, also in the trucks dead spot. This hazard could be solved by adding bike lanes next to the road, this means that the chance of a motorized vehicle being next to a bicycle is decreased. When it comes to priority it can give different rules to the cyclist, for example traffic light specially for the bicycles. The cyclists have more room and will not be in the dead spot of a truck. In this way cyclists have more room and cannot be in the dead spot of the trucks.

Adding a cycling lane can have a large impact on the safety of cyclists using that cycling lane instead of a regular road/intersection. According to a research of SWOV from 2013 the amount of injury accidents will decrease of 15% to 25% when going from a road without any cycling paths to a road with a -freestanding- cycling path. However these solutions are relatively costly and is estimated of €200.000 to €350.000 euros (14).

Signage unclear, cell phone needed to locate

Not every destination is mapped on signposts on the street, however to cycle quicker from point A to B it is easier to know in advance where you need to go instead of needing to stop at every intersection to know if this is the one where you need to turn left or right. To enhance the flow of the cycling travel, it is much easier to open google maps and find your route. However it's been proven that 3-4% of the bike crashes are due to the use of a phone and is therefore illegalized since July 2019 in the Netherlands (15). However, to make sure that there people also keep their phone in their pocket while driving on the F35, it might be convenient to add some road signs indication about some destinations, these could be names of neighbourhoods but also buildings such as supermarkets and the university. Adding these signs is relatively cheap (it would cost around €140 (16)) and also enhances the flow of cyclists.

Poor water management on roads

Due to lack of water drainage, a street can get flooded when heavy rain sets in. This results into a more slippery road but also a road which is difficult to see. As a cyclist the potential hazards arise that you can ride into the roadside, ride into a pothole or lose your grip at all. This can result into falling. Although it's very expensive to add more drainage under the streets (€150-200 a meter (17)), it is a potential solution to this problem. Another solution might be to higher the road slightly or to keep a small ditch next to it, in this way water can flow to the side before overrunning at all.

Road poorly lit roads

According to a research of SWOV the chance of getting into an accident during the night is 8 times higher than during the daytime (18). The increased chance of getting into an accident at night might be due to the fact that some cycling lanes are poorly lit, some lanes are lit by the streetlights from the road but at some points these are too far from the cycling lanes. This would especially be dangerous if there are intersections where another road user coming from the right or left is not visible. Adding street lights are relatively cheap and according to an estimation by Dutch program 'de Rekenkamer' the average cost of a street light would be around €800 (19). This can really benefit the safe situations around intersections.

Unclear or no line indication

Not every line indication of the road might be really necessary but at intersections these indications are very important. It says where every vehicle should go and the indications also give rules about priorities of traffic from the left and right side. If these lines are missing (maybe due to wear) it might not be clear anymore who has priority at the intersection. This is a very cheap solution to take care of. The price of line indication differs between €50 to €200 (20).

Lack of signage

A similar problem compared to the line indications. Signs can be unclear, due to dust or just barely visible at all. Streets signs are destroyed or go missing on a regular basis so it's important to keep track if they are always there and add more, this is also a relatively cheap solution around €140 (16) however there is someone needed to check if all the road signs are still there.

Infrastructure encourages high speeds

There are multiple reasons why a road would encourage road users to speed faster than the limit on that road. This could give a really dangerous situation since the speed limit is created for a reason. Road users should pay serious attention while driving and when someone is speeding, the brake time will increase, meaning that they handling adequately is impossible. Although it is difficult to find out if the cause of the accident was speeding, SWOV estimated that 4% of the accidents are due to speeding of a motorized vehicle (21).

There are multiple solutions for this problem. One of them is adding a speeding camera next to the road which flashes once somebody overreaches the speeding limit. However people only know they speeded after they have speeded while they should slow down in advance. The costs of theses poles are also relatively high, around €100.000 (14)

Other solutions would be by changing the infrastructure to minimize speeding, these could be speed bumps, but also adding lines to the sides of the road creating the illusion that the road is smaller which means people are slowing down.

Insufficient precautions for ice free roads

Since a lot of cycling paths are not meant for cars, the chances are not so big that these roads are getting brine spread during the icy/snowy days. However, according to research 28% of all single bike accidents are due to slippery road. So adding a small tractor to spread brine would decrease this hazard. The government also gave the cyclists an option to check out themselves if the roads are brined or not at 'routeplanner.fietsbond.nl'.

Split traffic flows

One of the most important aspects of collision control is too take out a collision between different types of vehicles altogether. An example of this can be the F35, where bikes are completely split from the car traffic. This creates the ultimate safety level for the Cyclist, while remaining and even improving traffic flows for both mobility groups. Splitting traffic flow can also be performed in much simpler and more applicable ways. An example of a simple application would be to add curbs before an intersection. These curbs protect the cyclist, because the car will feel immediate feedback when touching this curb. Therefore the car will have a safe distance to the cyclist.

Bicycle rider loses balance

In the single-bicycle accident FTA, it can be seen that there is a possibility that if a person is old and uses an E-bike there is a chance that the bikes loses their balance. This happens to be a serious issue. A solution for this issue is implementing borders on which they can hold their balance, e.g. a heightened curb or a fence to hold on to. This creates the opportunity for them to not need to dismount the bike, but keep being seated instead.

Future scenarios

A lot of solutions are now given corninging hazard reductions from the FTA. As seen in the analysis if these hazards are taken away some collisions can not occur anymore while others might simply be reduced. However a total new approach for designing intersections might be very sufficient to tackle multiple hazards at once. A possible structure might be that that there is a fence or stroke of grass between the road and the bicycle lane. So that bicycles are always separated from motor vehicles.

When there are no traffic lights and cyclists should decide for themselves if they could cross the road or not there should also be a stroke in the middle of the streets where cyclists (or pedestrians) could stop so that they only need to pass half a road at the time.

An even better solution would be a 'bridge' over a busy intersection so that cyclists would not even intersect with cars and trucks at all. Although this is the safest solution since you would completely skip all the hazards from the Car-bike collision FTA, this is a very expensive solution. The prices from cycle bridges differ a lot (€300.000 - €600.000) but an intersection bridge which would allow cyclists to go in any direction in Eindhoven costed around €6.300.000 (22).

Another problem that could arise in the future would be that a lot more people would use an e-bike or speed-pedelec. Since these bikes can go a lot faster than a regular bike but don't make a lot of sound they might be potentially dangerous because cyclists might not be expecting an e-bike overtaking them, which can cause people to scare up and then they might make unexpected movements. So in the future it might be handy to slightly widen the F35 (or other cycling lanes) and create different lanes, one for fast travel (like e-bikes or racing bicycles) and one for regular -normal- cyclists, who also might cycle with children.

But not only the environment could be improved, also the operators of e-bikes and speed-pedelecs. The increase of sold e-bikes is mostly due to an old-age group. However these are also the people which are more likely to be involved in an accident. The e-bikes might be overpowered and thus difficult to control. Since the speed-pedelecs could reach a speed of around 45 km/h it is important that it's not seen as a regular bike anymore but more like a new vehicle. People who want to buy such a vehicle should learn how to operate it and need a license to buy a speed-pedelec.

7. Monitor the system

The hazards identified in the FTA and FMEA should be monitored. As noted in the identification phase the design process presents a chance to control and prevent most hazards. In this design process, the probability of collisions can be decreased significantly. However, design decisions are made on more factors than safety alone. Sometimes the traffic flow is more important than marginal safety gains. Or the safer design option is simply too expensive and can therefore not be realised. Imagine the costs of separating all cycling traffic from other modes of transport. The costs would be astronomical. Designing for safety is therefore not a simple subject, as it always comes with tradeoffs to balance. It sometimes is about making the best *bad* decision. The best option for safety might be too costly, ineffective at handling higher traffic volume or not suited due to spatial limitations and therefore not a possibility. However, innovative and imaginary solutions should always be considered. Sometimes there are solutions that are innovative and have never been applied before, but are able to create real improvements for safety while being cost effective and perform as desired.

Based on these considerations, it is possible to formulate a design philosophy. This can be used as design rules of thumbs and should always lead to an optimal way to find safety for the users. The best options should be found and sometimes the best option can't be chosen, but the aim should be for a most perfect and complete solution in degree of safety, cost and traffic flow capacity. The design philosophy we propose consists of the following points, ordered most favoured to least.

1. **Separate** vulnerable cycling traffic from other forms of traffic completely by using;
    a. Separate cycling roads
    b. Bridges over dangerous intersections
    c. Restricting car flow in densely cycled areas
2. **Influence** behaviour of traffic users by implementing safety features
    a. Only give open and wide roads when traffic volume is low and cyclist rare
    b. Use high curbs and narrow twisty roads to slow car traffic down at bike crossings
    c. Implement safety features that support conscious decision making, such as traffic islands, heightened cycling ways and distinct line indication.
3. **Monitor** infrastructure such that it is in optimal condition
    a. Make sure that potholes, loose surface or slippery roads are kept to a minimum
    b. Invest time to evaluate whether traffic flows have changed and whether the infrastructure design still meets current demands
    c. Develop a safety culture where cyclists are aware of risks and car drivers respect the vulnerability of cyclists.

In the end, a proper safety design will be seamlessly integrated in the infrastructure. Users don't feel like they are actively being regulated but safety is improved nevertheless. Therefore;
"Safety by design is like a refrigerator—when it works, no one notices, but when it doesn't, it sure stinks."

We can therefore conclude that the best way to design for safety is to completely take out other traffic flows, so the collision between different types of transportation can never happen. This is not a real option for every intersection. However, dividing traffic flows just before an intersection could already improve safety a lot. Only a small curb dividing bike lanes and roads helps. In order to assess if a situation is safe enough the safety action table should be used Figure 6: Safety action tableFigure 6.

The safety action table scales the probability and severity of an accident, which could be based on result of a FMEA. When the severity of an accident is low, the probability of the accident does not really matter. When the severity is high, the accident should not happen at all. For example, a collision between a truck and a cyclist will have a high severity and should never happen. While a collision between a cyclist and a pedestrian is less severe and therefore can happen more often before action needs to be taken. The red parts of this matrix form the area where direct preventive measures are necessary. These risks can be identified leading, by using tools such as the FTA and FMEA to relate hazards to failure effects. The same is true for the dark and light yellow area, but with a lower priority. Situations that fall into the green area are safe enough in the current situation and demand no preventive measures.

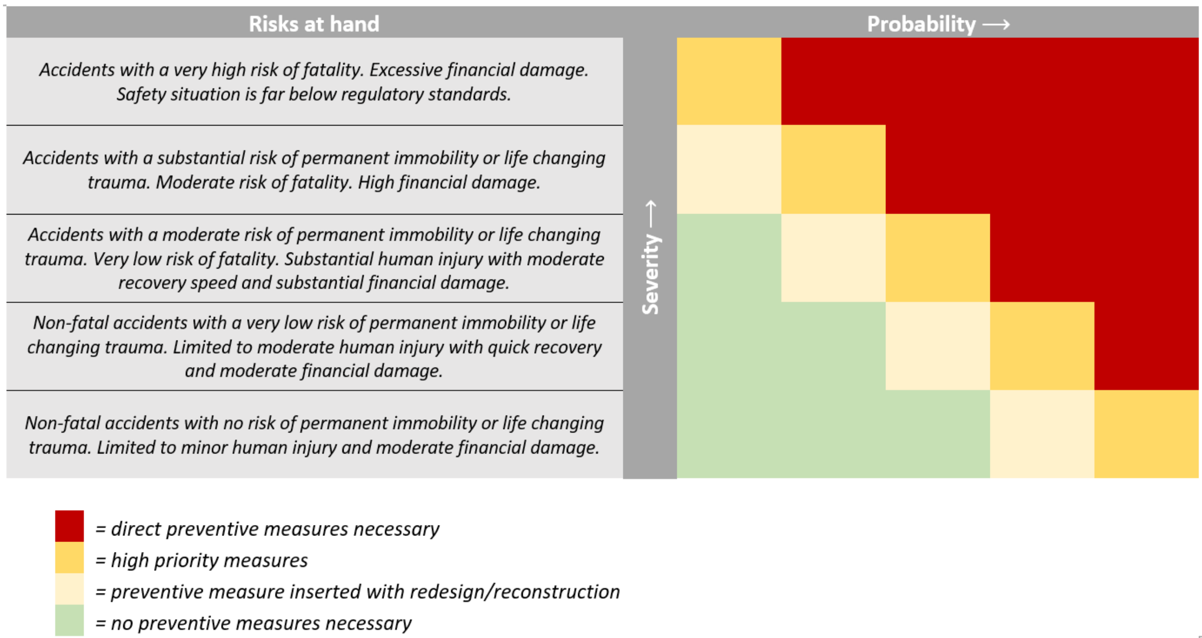


Figure 6: Safety action table

If preventive measures are needed, we refer to the design philosophy to be implemented. The more of this philosophy can be integrated, the safer the final situation will be.

Influence safety culture:

The safety culture can be influenced in many ways. There are ways to influence the user without them knowing but also using campaigns or using other regulations. One of the first ways to influence safety culture for bicycles is actually the children that get lessons on bike safety in their primary school. The way this is performed is by going out on the street in colonies and learning how to read the signs by practising and by learning the signs for the bicycle examination. Why would the government want to invest this money into this goal? This reason for this is that children most often need to go to their middle school by bike before they go to this school they only have to travel small and safe distances.

The government also influences users with marketing campaigns. An example can be the new regulation that phones are not allowed anymore on the bike. This is supported by marketing on television and in many other ways. Even a popular Dutch rapper is putting attention to this new regulation since it will make the accidents go down a lot for the younger generation.

A measure is taken already about 2 decades ago, that bikes are equally as important as vehicles was a big improvement in safety culture. This improvement at that time was a very interfering method to change the regulations within the traffic. Looking back at this decision, it can be evaluated as a great improvement for bikes. It even might not be considered as an interfering decision anymore. The users have no awareness of this intervention anymore. This makes this decision so remarkable.

Enschede wants to become the bicycle city of 2020. To achieve this goal, measurements have to be taken and some of them are already implemented in the city right at this moment. In this section, these choices are evaluated and some options for improvement can be given to make sure that the system will be safe for the bicycles coming in the next few years.

First of all, Enschede has built big parts of the F35 which improves mobility on the bike. Without the user knowing, this road creates a lot of safety. Of course, the user will see that by splitting the bicycles from the vehicles creates safety. The difference in speed on this bike lane is much lower and when a scooter wants to pass there is a lot of space to overtake. What the user might not know is that by creating a road that travels safe and fast, they are encouraged to the bike. The kilometres that they will bike on this road will make their skills improve, this will lead to a decrease in accidents because the user will have more experience. This is also a reason to invest more money into this project because it will increase safety in the short term and long term progression.

Enschede also works on the safety of bikes by making certain crossings more safe. The crossings now have all traffic combined without any barriers. The way to improve these situations is adding speed bumps, adding a small barrier for bicycles and other infrastructural measures to split different types of transportation and decrease the difference in speed.

8. Prove sufficient safety

In the problem definition it is stated that it is expected that cycling will remain an important mode of transportation in major cities. Growing cities such as Enschede need to innovate and improve the existing cycling structure to be able to support the increase in cycling traffic flow. Cities such as Utrecht and Amsterdam demonstrate that even with current trends in urbanization, cycling is an important factor in maintaining urban mobility.

To obtain insight into the ideal way of supporting this increase in cycling traffic flows, now and in the future, safety must be included in the project scope. If the cycling infrastructure is fast and has great coverage but is inherently unsafe, cyclists will not likely use the routes out of fear. It is therefore essential to have identified hazards and ways of monitoring and controlling them. These steps are already taken in previous chapters via various analysis methods. The question that remains is the proof of sufficient safety. To this end, we refer to our research question:

'How to systematically improve the safety of cyclists in Enschede by changing the infrastructural design of cycling routes.'

To systematically improve the safety of cyclists, thorough research into cycling incidents, causes and data analysis should be done. With the help of reports published commissioned by the Dutch Ministry of Infrastructure and Environment, data supplied by various institutes including the CBS and SWOV, a clear overview was created in which the hazards have been identified in a substantiated way.

By using safety process hazard analyses such as fault tree analysis and failure mode and effect analysis, these hazards have been mapped using the interrelations found in literature. By mapping them using logic, a clear overview is achieved that shows how and when hazards will lead to accidents. This was done for two main categories of cycling incidents, both car-bike collisions and single-bicycle crashes. By using the FTA it was found that in both cases, there are improvements that can be made to the infrastructure that have a great impact on the occurrence of incidents. Using the FMEA the risk priority numbers have been used to identify the most important effects of certain hazards. It became clear that nearly all incidents only occur when multiple other hazards are also present. Most notably is that infrastructure is in nearly any case one of those hazards.

From this we can conclude that a large amount of failures can be mitigated by using the systematic safety design approach. This is the reason we have created the design philosophy. A set of safety design rules for safer cycling infrastructure.

4. **Separate** vulnerable cycling traffic from other forms of traffic completely by using;
    a. Separate cycling roads
    b. Bridges over dangerous intersections
    c. Restricting car flow in densely cycled areas
5. **Influence** behaviour of traffic users by implementing safety features
    a. Only give open and wide roads when traffic volume is low and cyclist rare
    b. Use high curbs and narrow twisty roads to slow car traffic down at bike crossings
    c. Implement safety features that support conscious decision making, such as traffic islands, heightened cycling ways and distinct line indication.
6. **Monitor** infrastructure such that it is in optimal condition
    a. Make sure that potholes, loose surface or slippery roads are kept to a minimum
    b. Invest time to evaluate whether traffic flows have changed and whether the infrastructure design still meets current demands
    c. Develop a safety culture where cyclists are aware of risks and car drivers respect the vulnerability of cyclists.

The most important rules regard the infrastructural improvements that can be made during the design or redesign phases. These suggested methods are ranked from radical intervention to the lowest tier, where measures are more oriented towards maintenance and the development of a safety culture.

This last measure is an important one. It has been found that some of the accidents will occur even in safe infrastructure. This has to do mostly with the fact that people are not very well protected when cycling. If they lose their balance or fall because of a steering mistake, they will most likely end up with injuries from the impact with the road surface. Making the road surface soft enough so that people can fall on it takes away all the functionality of cycling in the first place.

A safe cycling culture is one where people feel safe and also see cycling as a great way of commuting. Because of this improved safety and image of cycling, people will be more likely to choose cycling over other transport modes and therefore increase their annual cycling distance. It has been shown by VeiligheidNL that the risk of injuries per cycling kilometre decreases if the cyclists commute regularly, both from single-bicycle and collision accidents. Innovations such as cycling highways, specialized infrastructure for cycling and incentives to use cycling as transport will all contribute to improved cycling safety, like Enschede is doing with the 'Fietsstad 2020' program. However, it remains important to choose the right design and critically analyse the solutions chosen. Therefore, we decided to put Enschede most prominent cycling feature, the cycling highway F35, to the test. To this end, several critical parts of the cycling highway will be analysed using the knowledge and insight gathered and of course apply our design philosophy.

9. Case studies

Enschede bike city 2020

In 2015, Enschede Showed a plan to create the F35 from the Lambertus Buddestraat to station Enschede Central. Part of this F35 was already existing. This bicycle lane is unique in the Netherlands, whereas this lane could be used to fast travel by bike from city to city in the region of Twente. Enschede is trying to become the Bike city of the Netherlands in 2020 and therefore different actions are taken:

- F35, to increase mobility in the region of Twente.
- Smart traffic lights, either controlled by rain sensors or controlled with smart GPS-location of bikers that are using the smart mobility app on their mobile.
- Rental locations for bikes throughout Enschede.
- Guarded bicycle parking in Enschede city centre.
- Deprecated bike lanes of bricks are renewed with layers of asphalt.

This case study is focussing on the safety aspects of the future Enschede city for bicycle users. Therefore, an analysis of the F35 will be given, including remarks on cost-effectiveness and flow rates of traffic. This is performed using the FTA analysis created in the report and the philosophy developed out of the results that are found.

Next to the evaluation of the F35, the study describes ways to improve the unsafe road crossings in Enschede. This is important since the research showed that this is a huge problem in Enschede.

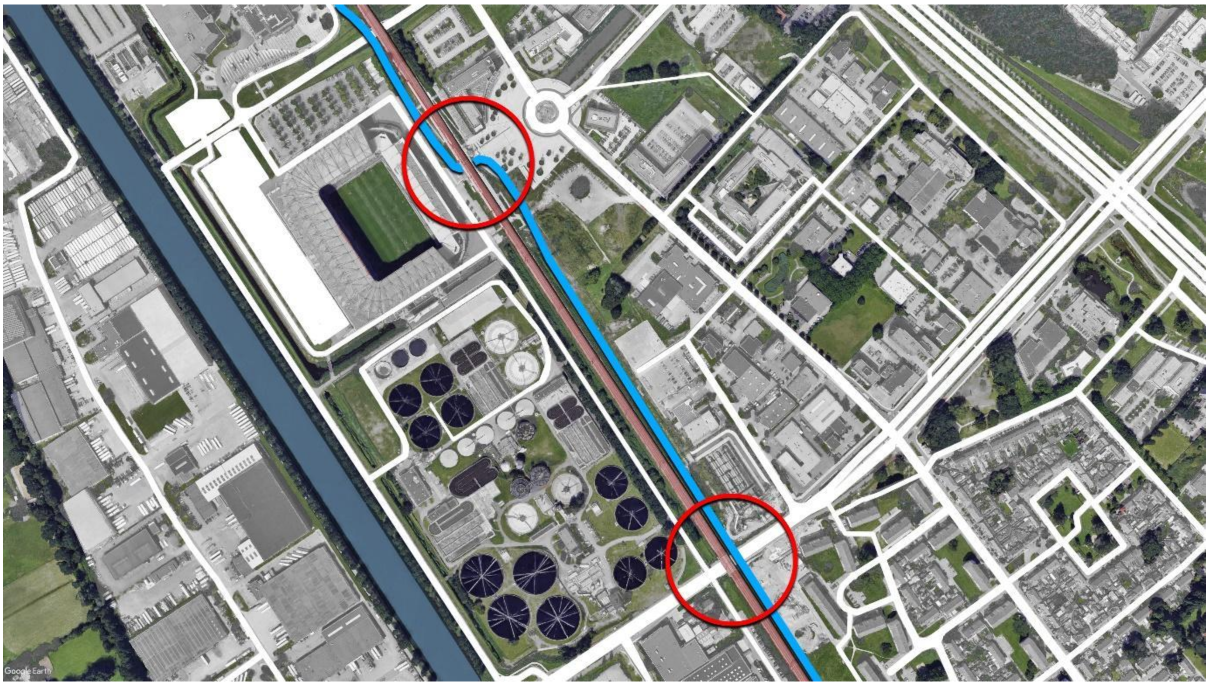
Lastly, although rental locations, guarded bicycle parking and smart traffic lights do not immediately increase the safety of bikes, study finds that biking experience is a huge factor in bike safety. The culture of making biking fun and creating extra opportunities for bike users is therefore beneficial for safety (3).

F35 Enschede

To analyse the F35, a report is found that describes what the F35 will look like in the future. To create an overview of the F35 in Enschede, the bike lane is sketched into the Google Maps images of Enschede. First, the part of from the Grolsch Veste to the Twekkelerzoom is discussed. This part is already a longer existing part of the F35 and is a direct connection of Enschede to Hengelo. The second part will be the from the Lambertus Buddestraat to station Enschede Central. This is also the part of which Enschede city made plans for in 2015 and will be finished in 2021. The last part is how the F35 will go north in the direction of Oldenzaal. This includes the newly built intersections just north of the central station. (SOURCE F35 LAMBERTUS STRAAT)

Grolsch Veste – Twekkelerzoom

While travelling from Hengelo to Enschede over the F35 the first thing that is recognizable is train station 'Kennispark', where the Grolsch Veste is the big eye-catcher. The F35 transfers from the West side of the train track to the East side of the train track. This happens under the train station. Because of the tunnel underneath the train track, the visibility for cyclists that make this transition is poor. The angle in which the cyclist goes down the slope to go under the train track bridge is very acute. A safety suggestion would be to make the angle in which the bicycle lane approaches the tunnel less steep, creating a better overview of the situation and reducing the speed of incoming cyclists. The FTA tree of a multiple vehicle collision is reassessed to match bikes and pedestrians collisions. The safety measure to split mixed traffic is not applied at this point on the F35. However, looking at the cost to benefits of adjusting this part of the F35, it can be seen that although a collision between a bike and pedestrian is possible, the severity might not be that high since the difference in speed is lower than a comparison of a car to a bike. The impact will therefore also be lower. Secondly, the F35 throughout Twekkelerzoom is a perfect example of a safe bicycle lane. A bike-car collision is impossible because there simply are no cars. Most hazards identified for single bicycle accidents are also minimized because the road is well maintained and there are safety precautions such as proper lighting and water management.

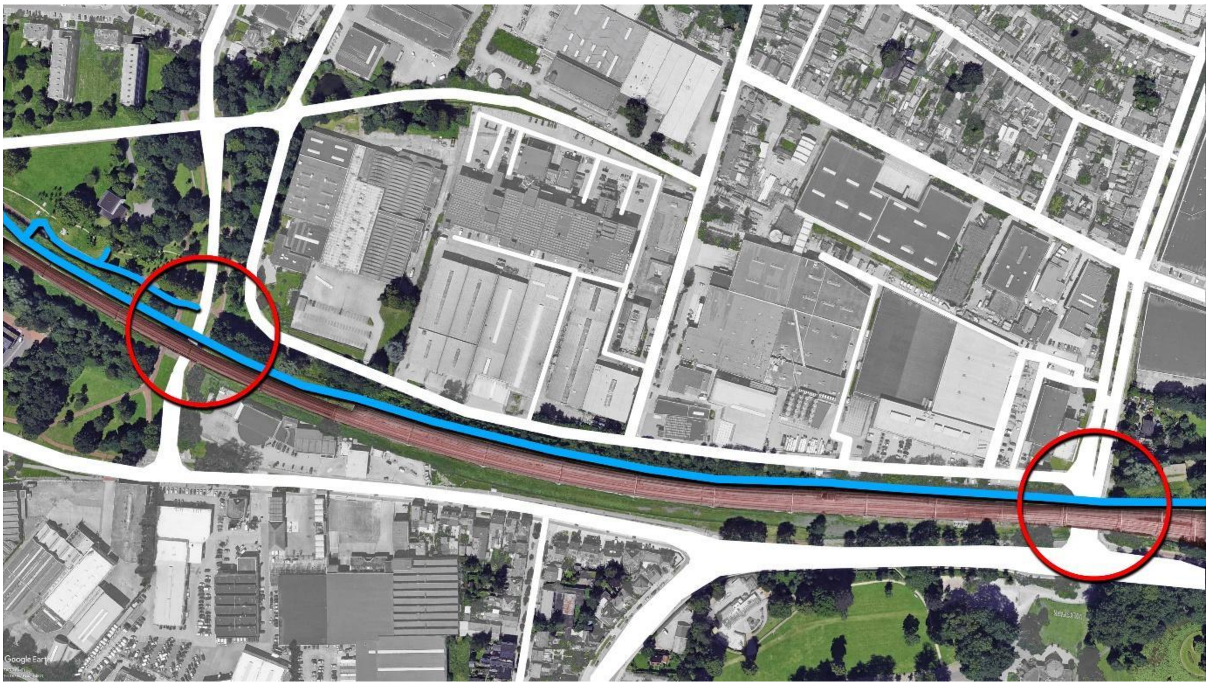


Lambertus Buddestraat - Station Enschede Central

This part of the F35 will be realized in the future. The plan is to start with building two bridges over the existing car roads in 2020 and to be realized in 2021. Creating a safe trip all the way from Hengelo to the Central station of Enschede. This whole section within Enschede is even completely splitting bikes and cars, thus creating no chance of a bicycle-car accident. In the picture below we find two red circles, first the situation in the circle on the left is discussed.

The Lambertus Buddestraat is the entrance in Twekkelerveld for traffic that coming from the highway in Enschede. At the North side of the train track, just after the train bridge, the bicycles out of the Western parts of Enschede need to cross this road. At this point the car roads have a high traffic flow making the current situation unsafe. The attention of the cyclist and car driver have to be optimal to maintain safety. The overview for cars coming from the South is compromised by the train bridge itself. Especially cyclist from the North-East are difficult to detect in time. The proposed solution, a bike bridge over this crossing will improve safety for the cyclist as well as improve the travel time for both cars as the bikers. The bridge might be expensive, but the traffic flow for cyclists will actually improve a lot. A proposed design is to completely take out the current crossing and move it 200 meters to the North. This measurement can increase traffic flow from the South and encourage cyclists to take the safe route over the road using the new bike bridge.

The second intersection located more to the East connects the North ring to the South ring around Enschede. This intersection is very chaotic for the users of the F35 right now, because there are three lanes for cars. Cars moving South are split into cars moving to the West and East. The third road are the cars moving to the North. The bikers need to cross three separate roads. The chance of a bike-car accident hereby becomes a real risk because the cyclist has to identify a safe crossing time for three rows at once, leading to a higher risk of error. Due to the bridge, cars will not be speeding because it blocks the line of sight to the traffic lights just after this crossing. However, in the current situations this is still is a dangerous crossing due to its complexity. This makes the bridge that will be built a major safety improvement.

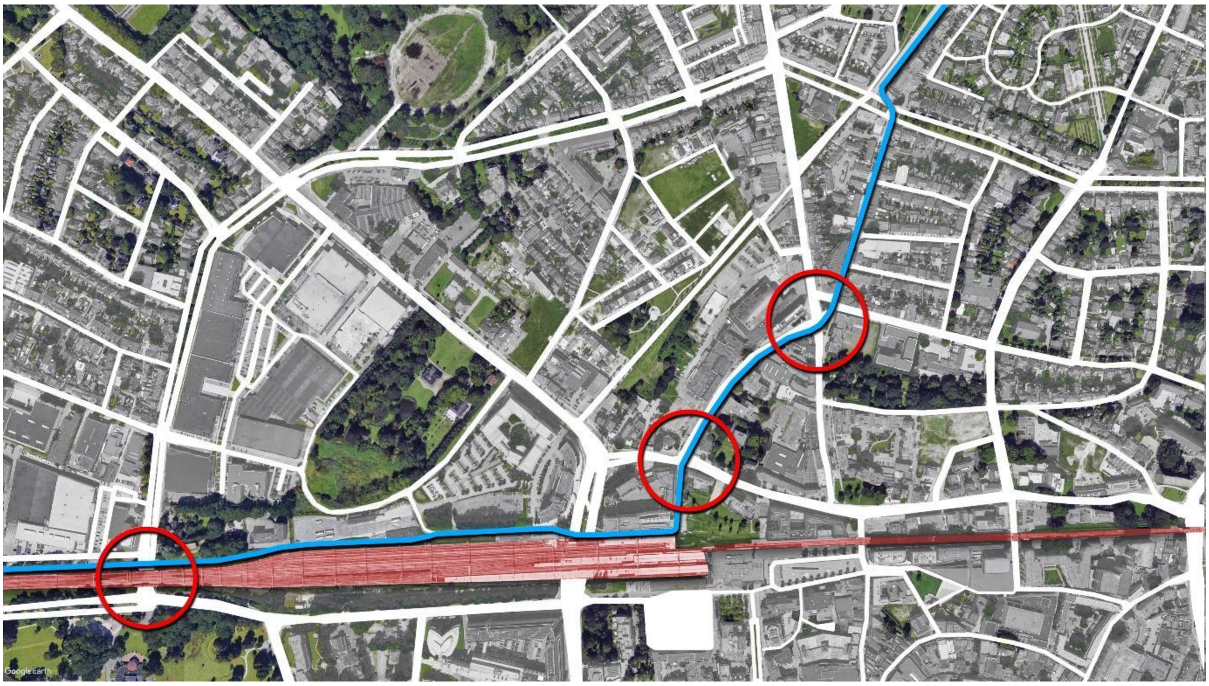


Central Station – Oldenzaal

The last part of the F35 in Enschede is to cross the Ruyterlaan and to get to the North of Enschede using the Brandweerstraat. The two most right circles in the map are the intersection of the Hengelosestraat with the Raffeisenstraat and the intersection of the Raffeisenstraat with the Deurningenstraat. In the previously discussed intersections, a bridge was decided upon so the traffic flows would be split. These two intersections are not splitting the traffic flows, but rather regulate it in such a way that the car traffic is redirected. In the future, Enschede aims to make the station square of central station completely car free and thereby also greatly reducing the car traffic flows over the Molenstraat.

For the first intersection with the Hengelosestraat, right of way had to change. This change in the right of way led to accidents on the opening day of the intersection. The F35, which crosses the Hengelosestraat, is heightened so the safety for cyclists is improved. The intersection is still very complicated. To sketch the situation right now, there are three directions a car can enter the intersection. The flow from West to North and vice versa have priority rights over the flow from the city centre (East). Bikes moving over the F35 also have priority over traffic that want to go to the city centre or the other way around. Then there is one remaining big stream of traffic flows which makes this intersection dangerous right now. The bikers that move from the city centre to the University of Twente. Because this group of traffic needs to wait for the road to free of cars, it can happen that there are multiple cyclists waiting to cross. Because there is no buffer before the intersection the F35 can be blocked by this. Also, the crossing of the road in the middle of a turn, while still needing to watch the car traffic flow coming from a parallel direction can be a challenge. When looking at the FTA of a multiple vehicle collision, it can be found that the traffic flows are not separated, the driver can be unaware of the bike presence and that the intersection is not designed for cycling traffic. Together this creates an unsafe situation.

The intersection will get safer with future plans to reduce car traffic on the Molenstraat, This is also encouraged by the intersection of the Raffeisenstraat with the Deurningerstraat, which does not allow cars to move to the West, making cars use the ring more often(23).



10. Conclusion

Dutch people use their bike more and more as main transportation, instead of a car or public transport. It is important to make the experience of riding a bike as safe as possible, so people keep motivated to use their bike. Over the last decades it can already be seen that the amount of deadly bike accidents has dropped significantly. This is a positive sign, but it should not hold back from further optimisation. There are still a lot of collisions and the safety of traffic could always be further improved.

Multiple researches and analyses were done in this report to find out what the hazards in the systems are and how these could be optimized. With the safety cube, it can be seen that the most hazard avoidance could be done in the super-system; the environment in which the bicycles interacts, these are the roads and intersections for example. The bicycles themselves are already optimized to a certain level and not a lot of enhancements could be done to them to make them any safer. However, the operator of the bike is also a cause of hazards due to distractions or not using the bicycle right (braking too late or not using the lights on the bike). These actions could be prevented by marketing campaigns, which are already used by the government today, contributing to a cycling safety culture.

Most hazards come from the super-system and to find out what these hazards are two different FTA's are made. One for a car-bike collision and one for a single-bike collision. Out of these FTA's it can be concluded that if cars and bicycles are always separated a lot of hazards are directly removed. Enschede has already done this right by creating the F35 (the bicycle highway). However, the intersections after the F35 are the ones that could be really hazardous. Our design philosophy focuses on separating the different traffic flows meaning that a collision between two types of vehicles cannot occur. Various other sorts of solutions can help to create less hazardous situations. Some of these solutions will help with improving the safety culture as well. This is especially beneficial because it does so with the people noticing the safety is improved in that way.

From a futuristic point of view it is important to look into the new vehicles that are at this moment seen as bicycles such as the e-bikes and speed pedelecs, since these are more powerful than a regular bicycle. There might be new rules implemented for these vehicles and also teach people more about how to use these faster bikes.

To answer our research question, 'how to systematically improve the safety of cyclists in Enschede by changing the infrastructural design of biking routes', we can conclude that it is possible to systematically design for safety. We suggest using our design philosophy as rules of thumb during the design or redesign phase. However, it is important to realise that mobility is very dynamic and that in the future this design philosophy should be evaluated and adapted to include unseen future changes. Infrastructure has a great impact on safety of cyclist and should therefore be always considered.

11. Discussion

In this report we have tried to create a design philosophy that changes the infrastructure safety for cyclists (especially in Enschede). This is done by doing multiple analyses to discover as many hazards as possible so that we could find a solution to these possible hazards. A whole report alone on only hazard identification could be made, we decided after a certain amount of time that there was enough information gathered to find solutions for the founded hazards. This means that there could be some hazards that might be overlooked or not taken into consideration because it does not fit the scope to be relevant in the Netherlands. To find more hazard more analyses could be performed. A good addition would also be input of the municipality of Enschede as well, because they might have different design ideations. Because this information was not made available, it could not be taken into consideration.

It's also difficult to predict the future scenarios, some predictions are easily made but it's not clear how the government will react to these future changes when it comes to E-bikes for example. The safety regulations might change drastically. To create a full solution which also works in the future it's important to implement multiple solutions for the FTA and some research should be done to find out its efficiency. This is one of the reasons the design philosophy is chosen as a 'final' product, this product should always be considered as a dynamic guideline. This means that this guideline might not be relevant for the future.

Lastly, it's difficult to completely make the biking experience as safe as possible because cycling is a dynamic situation which is always changing; bicycles are small - quickly - movable vehicles so cyclists always try to get as quick from point A to B. This means that sometimes they disobey the regulations and drive in places in which they are not allowed to such as the pavement, meaning that potential hazards arise which are unforeseen. So this might make it difficult to create a complete new intersection. Also cycling is always unsafe, since you're driving on two wheels and you have to react quickly when something happens.

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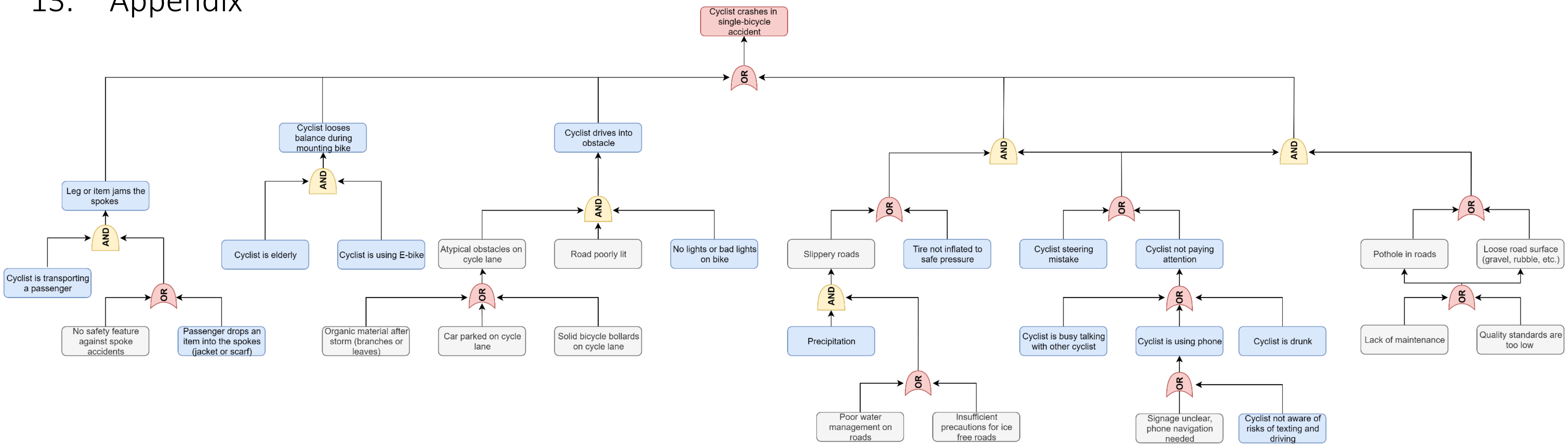
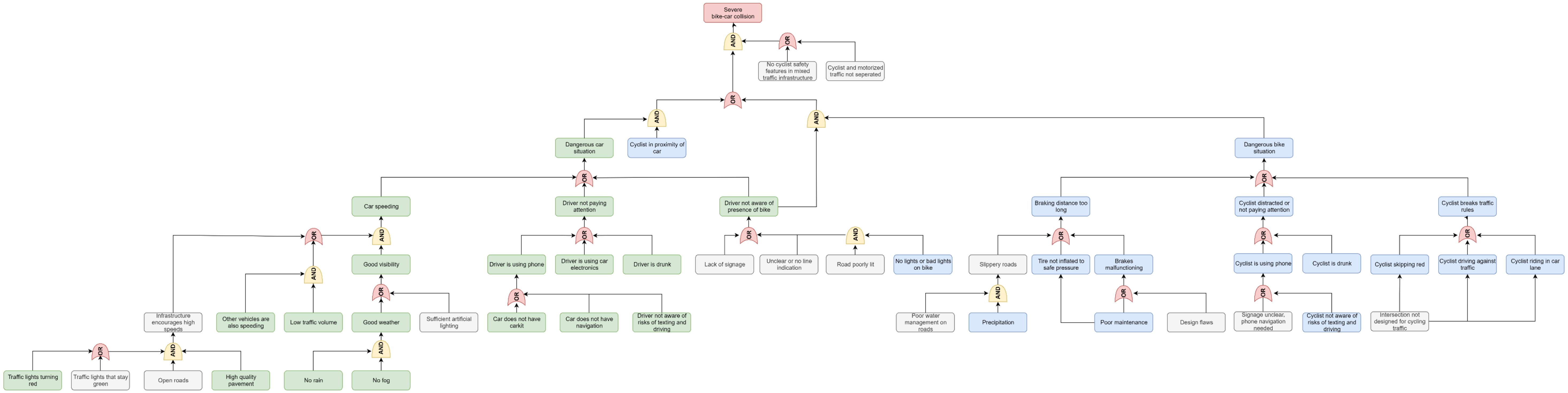
13. Appendix



Cyclist crashes in single-bicycle accident
OR
Leg or item jams the spokes
AND
Cyclist is transporting a passenger
OR
No safety feature against spoke accidents
Passenger drops an item into the spokes (jacket or scarf)
Cyclist looses balance during mounting bike
AND
Cyclist is elderly
Cyclist is using E-bike
Cyclist drives into obstacle
AND
Atypical obstacles on cycle lane
OR
Organic material after storm (branches or leaves)
Car parked on cycle lane
Solid bicycle bollards on cycle lane
Road poorly lit
No lights or bad lights on bike
AND
AND
OR
Slippery roads
AND
Precipitation
OR
Poor water management on roads
Insufficient precautions for ice free roads
Tire not inflated to safe pressure
OR
Cyclist steering mistake
Cyclist not paying attention
OR
Cyclist is busy talking with other cyclist
Cyclist is using phone
OR
Signage unclear, phone navigation needed
Cyclist not aware of risks of texting and driving
Cyclist is drunk
OR
Pothole in roads
Loose road surface (gravel, rubble, etc.)
OR
Lack of maintenance
Quality standards are too low



Severe bike-car collision
AND
OR
No cyclist safety features in mixed traffic infrastructure
Cyclist and motorized traffic not seperated
OR
AND
Dangerous car situation
Cyclist in proximity of car
OR
Car speeding
AND
OR
Infrastructure encourages high speeds
AND
OR
Traffic lights turning red
Traffic lights that stay green
Open roads
High quality pavement
AND
Other vehicles are also speeding
Low traffic volume
Good visibility
OR
Good weather
AND
No rain
No fog
Sufficient artificial lighting
Driver not paying attention
OR
Driver is using phone
OR
Car does not have carkit
Car does not have navigation
Driver not aware of risks of texting and driving
Driver is using car electronics
Driver is drunk
Driver not aware of presence of bike
OR
Lack of signage
Unclear or no line indication
AND
Road poorly lit
No lights or bad lights on bike
AND
Dangerous bike situation
OR
Braking distance too long
OR
Slippery roads
AND
Poor water management on roads
Precipitation
Tire not inflated to safe pressure
Brakes malfunctioning
OR
Poor maintenance
Design flaws
Cyclist distracted or not paying attention
OR
Cyclist is using phone
OR
Signage unclear, phone navigation needed
Cyclist not aware of risks of texting and driving
Cyclist is drunk
Cyclist breaks traffic rules
OR
Cyclist skipping red
Cyclist driving against traffic
Cyclist riding in car lane
Intersection not designed for cycling traffic