Safe cycling routes

Road safety indicators for cycling routes

R-2022-6A

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Prevent crashes
Reduce injuries
Save lives

Report documentation

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Contents of the project: This study deals with cycling safety on a route level. Firstly, it aims to define indicators to compare the safety levels of different cycling routes between a specific origin and destination. Secondly, it discusses how these indicators can be applied by road authorities in order to assess and improve the safety of cycling routes. And finally, it aims to discuss the function of different types of infrastructure in the cycling network, as elements in cycling routes.

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Summary

To ensure that the cycling network remains safe after an increase in cycling, a well-developed, safe cycling network is needed. Studies investigating safe cycling often focus on design choices at road level, whereas route and network levels are also relevant. This study deals with cycling safety at route level. Firstly, it aims to define indicators to compare the safety levels of different routes between each origin-destination (OD) pair. Secondly, it aims to discuss how these indicators can be applied by road authorities in order to assess and improve the safety of cycling routes. Finally, it also aims to discuss the function of different types of infrastructure in the cycling network, as elements in cycling routes. The study focuses on cyclist routes within urban areas (built-up areas).

Safe route indicators

Indicators were developed to compare the safety levels of different cycling routes. Safe route indicators that hadve been developed for cars in a previous study were used and adapted to cyclists based on a literature review and the application of the functional requirements and principles of Sustainable Safety to bicycle traffic. This results in the following indicators:

1. Travel distance as short as possible;
2. Travel time as short as possible;
3. Low intersection density, especially concerning intersections with distributor roads;
4. Wherever possible, cyclists should follow exclusive bicycle tracks;
5. Wherever possible, the use of 50km/h distributor roads without separate bicycle tracks should be avoided;
6. As few left-turns as possible;
7. As few transitions and discontinuities as possible.

These seven indicators aim to limit the exposure to potential risks and protect cyclists from motor vehicles. An additional eighth indicator, which is up for discussion, aims to protect vulnerable road users (pedestrians and vulnerable cyclists) from large volumes of fast-flowing bicycle through- traffic and other potential users of bicycle facilities:

8. Wherever possible, fast flowing and possibly heavy (high-weight) bicycle through-traffic should be separated from ‘residents’ and vulnerable bicycle traffic.

Although this eighth indicator is in line with suggestions from Fietsberaad and the Dutch Cyclists’ union, there is no evidence for the necessity of this additional indicator. Apart from the lack of evidence, there are some complications in operationalising and implementing the proposed indicator.

Improving safety levels of cycling routes

In order to improve the safety of cycling routes, road authorities can take measures at network level and at local level. Network-level measures include changing the network structure or functional role of links in the network. Measures at local level focus on the design of individual elements (road sections, intersections, transitions) in the network.

The eight indicators discussed above can be applied to identify locations in the network where cyclists' route safety can be improved. The first step is to carry out a network analysis in order to identify important cycling routes based on the existing travel demands and the network structure. The second step is to score the identified routes using the first seven route indicators discussed above. The scores can be visualised using a so-called route star. As a third step, different options can be identified to improve cyclist safety at route level. In general, there are three options: 1) existing routes can be made safer, 2) alternative safer routes can be created, or 3) safe routes can be made more attractive to cyclists. Moreover, a distinction can be made between measures at network level and measures at local level. The table below provides an overview of potential measures.

Network- and road-level measures for safe cycling routes

Approach	Measures for safe cycling routes
Network-level measures	› Separate motor vehicle flow traffic from access roads and bicycle traffic › Create direct cycling routes with minimal detour › Create exclusive bicycle tracks where possible › Create bicycle through-routes on exclusive bicycle tracks › Low motorised and bicycle traffic speeds on roads with strong exchange function › Introduce grade separation or avoid cycle route intersections with distributor roads › Avoid left turns and transitions between infrastructure types which require cyclists to cross with motorised traffic › Make safe routes more attractive to cyclists, for example by increasing comfort or adapting traffic light settings
Road-level measures	› Create separated bicycle tracks along distributor roads › Limit speeds where conflicts between cyclists and motor vehicles can occur › No obstacles in the cycling infrastructure › Sufficiently wide bicycle tracks › Quality surface: smooth, complete, clean, not slippery › Visual guidance › Forgiving track edges and verges

Function of different cycling facilities

The table on the next page shows the different types of cycling facilities and their function in the cycling network. Exclusive bicycle tracks are preferred for serving large volumes of (relatively high- speed) 'through' cyclists. Access roads, depending on their characteristics, can either be adapted to serve (larger volumes of relatively high-speed) through-traffic or mainly serve local bicycle traffic. Bicycle streets, while requiring further research into their safety and ideal characteristics, may be an option to serve flow cyclists on access roads when exclusive bicycle tracks are not feasible. Distributor roads are primarily intended for motorised through-traffic and can potentially serve a function for bicycle through-traffic as well. However, due to the high motorised traffic speeds it is important that physically separated bicycle tracks are present and intersections are minimised and as safe as possible.

Proposed functions of different cycling facilities in the network

Infrastructure category	Important characteristics	Primary function for motor vehicles	Primary function for cyclists
Exclusive bicycle tracks	› Wide enough to support variety of bicycle types and speeds › High bicycle traffic volume › Low adjacent pedestrian volumes › Few intersections, side-roads › Safe track-side verges › Bidirectional bicycle traffic	n/a	Flow
Access roads: flow	› Potential bicycle streets › Low motorised traffic speeds › Low motorised traffic volumes › Minimal exchange traffic › Few intersections, side roads	Exchange	Flow
Access roads: exchange	› Traffic calming › Lower cycling speeds to protect vulnerable cyclists and pedestrians › Low motorised traffic speeds › Low motorised traffic volumes	Exchange	Exchange
Distributor roads	› Separate bicycle track › Uni- or bidirectional bicycle traffic › Avoid at-grade intersections	Flow	Flow

Recommendations for further research

A few areas have been identified for further research. First, while the first seven indicators have each been shown to have a relation with bicycle safety, the combination of this particular set of indicators into a total route safety score has not been validated and weight factors have not been determined yet.

Second, there is no scientific evidence yet for the eighth indicator. Further research related to this indicator could for example focus on causes and nature of bicycle crashes without motor vehicles. Regarding the feasibility of this indicator, future research may also investigate the relation between variation in cycling speeds and types of cycling facilities.

Third, additional research is needed in relation to bicycle streets. Bicycle streets are implemented in increasing numbers and may be an option to serve flow cyclists on access roads However, there is large variation across current bicycle street designs and more research is needed to determine their impact on cyclist safety.

Contents

1 Introduction 9

1.1 Background: road, route and network level 9
1.1 Study objectives 12
1.2 This report 12

2 Indicators for safety of cycling routes 13

2.1 Literature review on cycling safety 13
    2.1.1 Cycling safety at the network level 14
    2.1.2 Cycling safety at the route level 16
    2.1.3 Cycling safety at the road level 18
2.2 Sustainable Safety 21
    2.2.1 Sustainable Safety principles 21
    2.2.2 Sustainable Safety applied to bicycle traffic 21
    2.2.3 Sustainable Safety at the route level 26
2.3 Route safety indicators for cars 27
2.4 Synergy: indicators for the safety of cycling routes 29
    2.4.1 Identified indicators 29
    2.4.2 Separating bicycle through-traffic? 30

3 Application of safe cycling indicators 33

3.1 Introduction 33
3.2 Network level application of safe cycling indicators 34
3.3 Network level measures 36
    3.3.1 Function of different cycling facilities in the network 36
    3.3.2 Reducing conflict points and exposure 38
    3.3.3 Route attractiveness 39
3.4 Road level measures 39
    3.4.1 SPI’s: Sufficiently safe road infrastructure 39
    3.4.2 SPI’s: Sufficiently safe bicycle tracks 40
3.5 Example network from Utrecht 42
    3.5.1 Network analysis 42
    3.5.2 Route safety assessment 45
    3.5.3 Upgrading the network 47
3.6 Summary 53

4 Conclusions and recommendations 54

4.1 Conclusions 54
    4.1.1 Safe route indicators 54
    4.1.2 Application of indicators 55
    4.1.3 Function of different cycling facilities 55
4.2 Recommendations 56
    4.2.1 Recommendations for policymakers 56
    4.2.2 Limitations and recommendations for further research 57

References 59

Appendix A Translations 66

Appendix B Safe cycling indicator calculations 67

1 Introduction

This report discusses indicators for the safety of cycling routes and measures that road authorities can take to make cycling routes safer. The focus of the study is on cycling routes inside built-up areas. This chapter provides the context and main research questions.

Cycling is an attractive alternative to other modes of transport. It promotes a healthy lifestyle, is more cost-effective than passenger cars or public transport, is faster than walking, takes less space on the road compared to cars and public transit, and is more beneficial to the environment. This has led to an increase bicycle use in many cities (Pucher, Dill & Handy, 2010; Schepers et al., 2021). On the other hand, along with this increase in urban cycling, concerns about cyclist safety have been growing due to increased numbers of cyclists involved in serious road crashes (Adminaité-Fodor & Jost, 2020). In the Netherlands, the number of cyclists involved in fatal and severe crashes has also increased in the past ten years, and their share in these crashes is the largest of all transport modes (Aarts et al., 2021).

To ensure a safe increase in cycling, it is necessary to have a well-developed cycling network. It is known that cycling infrastructure, like separated bicycle tracks, helps to increase cyclist safety (Van Petegem, Schepers & Wijlhuizen, 2021). Studies investigating safe cycling often focus on design choices at the road level, whereas also the route and network levels are relevant. These possible levels of analysis are discussed in more detail in *Section 1.1*. Subsequently, *Section 1.2* presents the objectives of this study and *Section 1.3* provides the structure of this report.

1.1 Background: road, route and network level

Infrastructure safety or performance can be evaluated at a wide range of scales: from the shape of a curb, to city or even country level analysis. For each scale of analysis, different types of indicators can be used. Three general scales of analysis can be identified: the network, route, and road level (see *Figure 1.1*). At the scale of a road, three types of infrastructures can be studied: road sections, intersections, and transitions between road types or road categories. These five levels of the traffic system were defined as follows by Janssen (1997):

1. **Network**: all road categories, road sections and intersections together as a whole
2. **Route**: a combination of road sections and intersections between an origin and destination
3. **Road**:
    - 3a. *Road section*: a single (part of a) street falling under one road category, often connecting two intersections. Road categories include access roads, distributor roads, and through roads
    - 3b. *Intersection*: a place where two or more road sections, possibly from different road categories, meet and where turning is allowed
    - 3c. *Transition between categories*: the function of a road can change along one road section. A place where this happens is, for example, on the border of a built-up area. When a road section crosses this border, the road category can change from access road to distributor road. For cyclists this can mean that a bidirectional bicycle track becomes a unidirectional

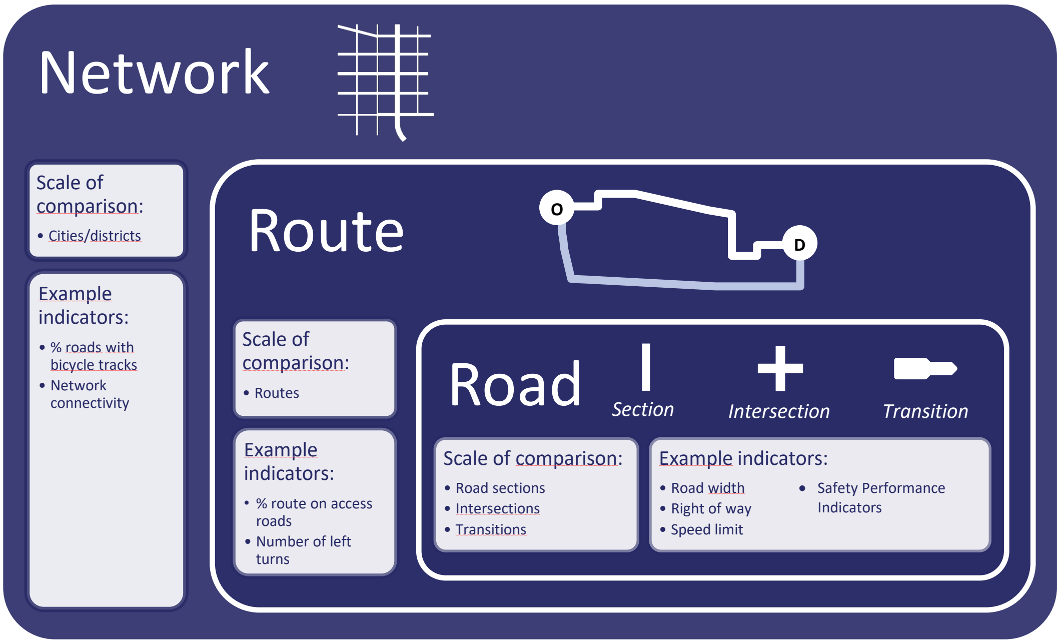


Figure 1.1. Scale of infrastructure analysis.

Network

At the network level, the level of analysis is most aggregated to a group of road elements over which many different routes can be taken between various origins and destinations. The scale is typically of a district, city, or even a larger level. Different types of indicators may be calculated: first, there are indicators which measure the structure of the network and can only be calculated at the network level. Secondly, aggregated indicators can be calculated for the network based on the road-level characteristics of all elements in the network.

From a network planning perspective, it is also relevant to consider how the network functions as a whole serve mobility demands. Different roads in the network can serve different purposes: to move through-traffic (flow function), or to access locations on the road (exchange function). Planning at the network level for the function and positioning of roads is necessary to guide traffic flows to follow routes which ensure the most safety for all road users, including the clear separation of functions.

To assess network performance or compare networks with each other, examples of network-level indicators include aggregated road level characteristics (e.g. % of network length with bicycle infrastructure), traffic volume data, connectivity of the bicycle network, or average travel times/accessibility may be used. For a description of studies into cyclist safety at the network level see *Section 2.1.1*.

Route

A route is defined as the set of links (road sections) and nodes (intersections) taken to travel from a certain origin to a certain destination. For each origin-destination pair (OD-pair), there are different routes that can be taken. At the route level, the focus lies on characteristics of an entire route taken between a given OD-pair, compared to other available routes (“route alternatives”) between the same OD-pair. Different routes will have different characteristics; for example, for one OD-pair there may be the fastest route, safest route, most direct route, or more scenic route. The various routes between one OD-pair have different safety levels.

The characteristics of available routes depend heavily on the characteristics of the road elements as well as their function within the network. However, even if the road sections, intersections, and transitions are ideally designed for the function they have, there may still be differences between the safety of two routes; this may, for example, be due to differences in length of the routes, road categories (e.g. access roads vs. distributor roads) or number of left turns.

Indicators which are typically evaluated at the route level include route distance, number of (left/right) turns, number of signalised intersections, as well as road level characteristics aggregated to the route level (e.g. 50% of the route uses a separated bicycle track). Instead of comparing one specific road design with another, entire routes are compared with alternative route options to evaluate their safety. For a description of studies into cyclist safety at the route level see *Section 2.1.2*.

Road (sections, intersections, transitions)

At the road level, the focus is typically on comparing specific design choices. At this scale, three network elements can be distinguished (Janssen, 1997): road sections (the links within a network), intersections (the nodes connecting multiple road sections), and transitions (points along a road section where the road changes from one type to another). Road sections accessible to cyclists can belong to one of three primary categories depending on their function within the network: exclusive bicycle tracks, distributor roads, and access roads (see *Table 1.1* for a description). Through-roads are generally not accessible to cyclists due to the very high speeds and are therefore not considered as a route option for cyclists. Regarding cycling infrastructure, there are exclusive bicycle tracks, separated bicycle tracks, bicycle lanes and mixed traffic conditions with bicycle streets as a special, unofficial type. A bicycle street is a street in which cyclists are considered to be the most important road users; cars are allowed, yet, considered to be ‘a guest’ in these streets.

Table 1.1. Categories of road sections accessible to cyclists within the built-up area

Road section categories	Speed limit	Description
Exclusive bicycle track (Dutch: “*solitair fietspad*”)	n/a	Bicycle track that is not next to a road, also referred to as ‘solitary bicycle track’.
Access roads (Dutch: “*erftoegangsweg*”)	15 km/h, 30 km/h	Offer direct access to residential areas at the locations of origin and destination
Distributor roads (Dutch: “*gebiedsontsluitingsweg*”)	50 km/h, 70 km/h	Connect the through roads with the access roads. The traffic flows on road sections and exchange occurs at intersections.

Examples of indicators which may be evaluated at the road level include the road profile (width, types of different facilities on the road), road material, the presence of cycling facilities (e.g. bicycle track, bicycle lane), or different ways of managing priority at intersections. Specific design elements at the road level which have been found relevant to road safety are also identified as what are called Safety Performance Indicators (SPIs), which can be used to estimate and monitor the safety level of roads within the traffic system (Kennisnetwerk SPV, 2020b). For a description of studies into cyclist safety at the road level see *Section 2.1.3*.

1.1 Study objectives

This study deals with cycling safety on a route level. First of all, it aims to define indicators to compare the safety levels of different routes between one OD-pair. Thereby the focus is on indicators on a route level rather than the crash rates on the individual road sections and intersections that are part of the route. Second, it aims to discuss how these indicators can be applied by road authorities in order to assess and improve the safety of cycling routes. Finally, it also aims to discuss the role of different types of infrastructure in the cycling network as elements of the cycling routes. The focus of this study is on cyclist routes within urban areas (built-up areas).

1.2 This report

The next chapter discusses the development of indicators to compare the safety level of cycling routes. The indicators are based on literature, the Sustainable Safety vision and indicators that were developed to compare the safety level of car routes. *Chapter 3* subsequently discusses how these indicators can be applied to compare the safety of alternative routes and which measures road authorities can take to make cycling routes safer. *Chapter 3* also discusses the role of different types of cycling infrastructure. *Chapter 4* presents the conclusions and recommendations.

2 Indicators for safety of cycling routes

This chapter presents eight indicators for the safety level of cycling routes. The indicators are based on Sustainable Safety principles, indicators used for the safety level of car routes, and indicators found in past literature relevant for cyclist safety. The first seven indicators aim to limit exposure and potential conflicts with motor vehicles. The eighth indicator is for discussion and poses the question whether bicycle through-traffic should be separated from all other traffic as much as possible.

This chapter presents indicators to compare the safety levels of different cycling routes (*Section 2.4*). These indicators are based on a literature review on cycling safety that is discussed in *Section 2.1*, Sustainable Safety (*Section 2.2*) and indicators that have been developed in earlier research to compare the safety of different routes for car traffic (*Section 2.3*).

2.1 Literature review on cycling safety

The literature on cycling safety can be categorised into three levels (see *Section 1.1*): studies that evaluate safety at a large-scale network level, at a more detailed route level, or at a more microscopic level: intersections or road sections.

Both national and international literature on cyclist safety was reviewed. A literature review that was carried out in 2021 was used as a basis (Nabavi Niaki, Wijlhuizen & Dijkstra, 2021). As the current study focuses more particular on cyclist route safety, additional literature on this topic was sought. Keywords related to cycling, safety and route were used. For example, “cycling route safety” yielded about 11,800 results on Google Scholar, and “safety of cycling routes” gave 482,000 results. After reviewing the publication title and abstract, from the first 5 pages of results, relevant papers were selected for further study. Redefining the search term to “bicycle* OR cycl* AND rout* AND safe*” and “bicycle* OR cycl* AND path AND safe*” led to 5,808 and 1,751 results of which a large share was from other disciplines. The first 20 pages of the first term were inspected, from the latter the first 15 pages. The found studies not only included route choice studies, but also included studies investigating the safety of routes in a network. Route choice studies were excluded, since they mostly lack a safety evaluation method which makes them less related to the purpose of the present study. In addition, cycling safety studies that were not route-related were also excluded from the list of reviewed literature. Finally, studies that covered the safety of cycling routes were pooled. In total, 92 studies were found that were published from the late 1970s, for more detailed reading of the articles. The reference list of the most interesting studies was also scanned for relevant articles.

The following sections briefly highlight the research efforts made on cycling safety at all three levels.

2.1.1 Cycling safety at the network level

When searching for network-level studies, several ways of approaching the network were found. One approach investigates the cycling network as a whole and assesses the structure and safety of this cycling network with network-level indicators. Another approach evaluates the cycling network based on the sum of all road section and intersections, called the aggregated road-level indicators. Lastly, a study about unbundling the cycling network and motor vehicle network is discussed.

Network-level indicators

One way of investigating the safety level of a cycling network is by using the network as a whole. Osama and Sayed (2016) assessed the impact of the cycling network structure on cycling safety in Vancouver, Canada, using the following indicators:

- Connectivity
  - network density: length of cycling network divided by length of road network
  - degree of connectivity: number of bicycle links divided by the possible number of street links
  - network coverage: number of bicycle links divided by the actual number of street links
  - intersection density: number of intersections over travel area
  - complexity: the average number of bicycle links per node
- Directness
  - linearity/orientation: ratio between a crow's flight line and its effective straight line (offsets curves, road bends, and forced turns)
  - continuity: average road section length (between two nodes)
- Topography
  - cycling facility length: length of cycling facilities regardless of type
  - grade: average slope of links with cycling facilities

They reported that higher levels of connectivity increase the probability of a cyclist-vehicle crash. The authors explain this result by arguing that it is likely that more network links between nodes indicate more frequent routes, which may result in higher exposure to conflicts and consequently more crashes. Moreover, some of the variables in this category represent interruptions along the road network, which may also increase the probability of a crash. For example, the higher risk of cyclist crashes with higher intersection density has been established in other literature (Siddiqui, Abdel-Aty & Choi, 2012; Wei & Lovegrove, 2013). Measures of directness, and topography were shown to decrease the likelihood of a cyclist-vehicle crash.

Another study, conducted by Zhang et al. (2015), also investigated the effects of road network structure on cyclist and pedestrian crashes in Alameda County, California. The structure of the road network was represented by:

- Average geodesic distance: the average number of links along the shortest path
- Network betweenness centrality: based on the frequency with which a point falls between pairs of other points on the shortest paths connecting them, in other words, it assigns weights to roads based on how the roads are connected – a grid system has a lower value since all roads are equally important, whereas a non-grid road network with many cul-de-sacs has a higher value
- Overall clustering coefficient: road clusters are defined as how roads are connected within a network

They found that longer average geodesic distance, higher network betweenness centrality, and a larger overall clustering coefficient were related to fewer vulnerable road user crashes. The first indicator, average geodesic distance, provides contradictory results compared to other studies stating that a higher intersection density is safer for vulnerable road users (Osama & Sayed, 2016; Siddiqui, Abdel-Aty & Choi, 2012; Wei & Lovegrove, 2013). The Network betweenness centrality indicator shows that if there are more access roads compared to collector/arterial roads, there are fewer crashes for vulnerable road users. Finally, the overall clustering coefficient shows that when there are many road clusters (where roads are well-connected between themselves, but badly connected to other clusters), there is a lower crash frequency for vulnerable road users. In general, the results from these variables show that local roads and residential areas have lower crash frequency for vulnerable road users.

A more recent study by Kamel and Sayed (2020), also evaluated the structure of road networks and their effects on cyclist safety. Some of the relevant variables they used include:

- Centrality: represents network inter-connectivity and accessibility
    - degree of centrality: measures to what extent a node is connected directly to other nodes
    - betweenness centrality: a higher weight is given if a node is positioned between several other nodes
    - closeness centrality: a node is central if a node is near to all the other nodes along the shortest paths
    - straightness centrality: a node is central if the paths connecting node i and many other nodes are straight
- Network complexity: ratio between the network diameter and the length of the network
- Network connectivity
    - network density: length of cycling network divided by length of road network
    - intersection density: number of intersections over travel area
- Network directness
    - linearity: ratio between a crow line and its effective straight line (offsets curves, road bends, and forced turns)
    - average edge length: total length of the bicycle network divided by the number of links in each TAZ
- Topography
    - cycling facility length: length of cycling facilities regardless of type
    - grade: average slope of links with cycling facilities

The results from this study indicate that bicycle network length, centrality, assortativity, and continuity decrease the number of bicycle–motor vehicle crashes, while bicycle network length and network continuity are expected to increase bicycle kilometres travelled. On the other hand, the bicycle network complexity and development, connectivity, and linearity increase the number of bicycle–motor vehicle crashes.

The studies mentioned above all use the graph theory method to evaluate the suitability and safety of the whole cycling network and do not focus on specific infrastructural elements. These studies were presented to show how different methods use very different variables and measures to evaluate cycling safety at the network level. Related to our study, the cycling facility length and intersection density seem interesting and adoptable variables to use for route safety evaluation.

In addition to that, these studies were conducted in North America, where the cycling infrastructure, network, and culture are very different from the Netherlands. Therefore, the results probably cannot be directly transferred to the Dutch situation.

Aggregated road-level indicators

In addition to the network-level indicators, the safety level of a cycling network can be investigated by taking the sum of all road sections and intersections. To evaluate the safety of a cycling network, some indexes have been proposed, each of which considers a wide range of indicators (Callister & Lowry, 2013). Most of these methods summarise the safety of a network as the sum of all its parts (focusing on road sections and intersections). For example, Bicycle Safety

Index Rating (BSIR) is calculated by combining the Roadway Section Index (RSI) and the Intersection Evaluation Index (IEI). The variables used to calculate the BSIR include the posted speed limit, traffic volume, presence of parking on road, number of road lanes, road lane widths, type of signalization, presence of right and/or left turn lane, permission to turn right when red-traffic light, road shoulder widths, road shoulder pavement type, road pavement condition, curb radius, number of driveways, restricted sight distance, raised median, road grade, and surrounding land use (Davis, 1987). The Bicycle Score (BS) method proposed by Winters et al. (2013), uses indicators such as cycling facility type and length, road grade, land use, and intersection density to evaluate the bikeability of a road network. Other methods adopted to evaluate the cycling network have been found, but their focus was not on safety, e.g. Bicycle Compatibility Index (Harkey, Reinfurt & Knuiman, 1998), Bicycle Stress Level (Sorton & Walsh, 1994), Level of Traffic Stress (Mekuria, Furth & Nixon, 2012), Bicycle Level of Service (Transportation Research Board, 2016), Bicycle Environmental Quality Index (San Francisco Department of Public Health, 2009), Metropolitan Cycling Network Planning (Milakis & Athanasopoulos, 2014).

Unbundling
Unbundling, in the context of cycling safety, is defined as the separation of road and cycling networks. The goal of this approach is to reduce (possibly eliminate) interactions between cyclists and motor vehicles. Although the road and cycling networks are usually fully integrated, it is possible to reach certain levels of unbundling.

According to a study by Schepers et al. (2013) unbundling can be achieved when:

- intersections accommodating vehicles and cyclists are grade-separated;
- cyclists prefer to ride on access/residential roads where there is less vehicular traffic and lower speeds (as a result of traffic calming measures implemented for vehicles);
- cycle tracks (physically separated from other road users) are provided on distributor roads;
- exclusive bicycle tracks (where motor vehicles are not allowed) are implemented.

Each of the mentioned features have been individually studied in the cycling safety literature and are discussed in *Section 2.1.3*.

Schepers et al. (2013) tested the hypothesis that unbundling corresponds positively with cycling safety. In their analysis, historical crash data (2004-2009) was used, as well as a variable combining access road usage and grade-separated intersections to represent unbundling. In order to estimate the expected number of crash victims, they adopted a crash prediction model controlling for kilometres travelled by bicycle and car, age of crash victims, and population density of municipalities.

Results from employing a Negative Binomial Regression model showed that the likelihood of cyclists being hospitalised or killed is lower in municipalities with a higher degree of unbundling. More specifically, they found that increasing unbundling by 1 standard deviation results in a 24% reduction in chance of fatality and 15% in chance of serious injury (Schepers et al., 2013).

2.1.2 Cycling safety at the route level

Most of the papers about route safety did not actually evaluate the safety of cycling routes. The word “route” is used differently, sometimes to indicate a whole cycling network and sometimes to indicate a cycling facility. Allen-Munley, Daniel and Dhar (2004), for example, write about urban bicycle route safety in a similar way of how route safety is discussed in the present study. However, the employed analysis focusses on evaluating the safety of separate road sections, which results in a cross-sectional study rather than a route safety study. Furthermore, in some studies the focus was on subjective safety rather than on objective safety. For example, the study “How do we know if walk and cycle routes are safe?” is a study on cyclist and pedestrian safety perception while interacting with traffic (Stark, 1996). The study by Cedersund (1979), established the following route variables: road cross-section, environment, distance between junctions, cycle track/no separated cycle track and speed limit. He found that accident rate was highest when the distances between intersections were smaller (which means a higher intersection density was found to be less safe), and cyclists were closer to the town centre. They did not, however, take traffic flows and pedestrian/cyclist flows into consideration.

More recent studies investigated the safety of routes in a network with complex route prediction and safety models. Chandra (2014) created a multi-objective shortest path algorithm that selects an optimal path in terms of safety and travel time from a set of route options between an origin and destination. Safety is evaluated based on potential risk of having a crash involving an older driver or cyclist with other vehicles. Two safety indicators were developed; one to assess the safety of streets and one to assess the safety of intersections. Several traffic attributes, like speed and density, driver attributes, like perception-rection time, and street attributes, like length and tire-to-road friction are used to create the safety indicators. The safety indicators are a quantification of the crash potential of a vehicle of cyclist when it drives on a street network. For streets, the safety indicator quantifies how safe two vehicles or cyclists are while traveling on the same street at the same time. For intersections, the safety indicator is evaluated by the time used by a subject vehicle to approach an intersection at one of the connected legs. The aim of the algorithm is that it presents a route that avoids road sections and intersections that have high safety indicator values when a vehicle or cyclist travels from a given origin to a known destination. With the safety indicators it is possible to rank streets and intersections of different types of networks. In the study by Chandra (2014), the model was tested on the network of the City of College Station, Texas, USA, which is part of a larger urban network suitable for both cars and bicycles. While the algorithm was tested for two types of road users, an older car driver and a younger cyclist, we focus on the results for the cyclist. From ten tested routes, the algorithm chose the safest and fasted route based on the safety indicators explained above. Important to mention is that for both older car drivers and for younger cyclists the safety indicators are calculated in the same way. However, the calculations lead to different results for these two types of road users.

In the area of predicting bicycle flows at the network-level, Cooper (2017) created a Spatial Network Analysis (SpNA) methodology and tested this model to find out if it leads to similar results as actual bicycle flow data. The model treats route choice decisions of car users and cyclists separately, which makes it useful to investigate the interactions between cyclists and motor vehicles. This is also tested in our study. The final model to predict bicycle flows is a combination of trip generation, trip distribution, mode choice, and route choice models. The resulting bicycle and motor vehicle flow predictions are used in a road safety model based on crash data. The road safety model predicts crash probability based on the presence of both cyclists and motor vehicles in large numbers on the same road section. The outcome of the road safety model is a ‘conflict score’, which is used as a binary classifier to categorise a road section as either low-risk or high-risk. The final road safety model predicted 75% of the crash sites and 73% of the non-crash sites. It is beyond the scope of this report to explain every detail of the SpNA methodology. Please refer to Cooper (2017) for a thorough description of this model.

In London, four cycling routes, the Cycle Superhighways, have been realised in 2010 and 2011 to promote commuter cycling by providing safer, faster and more direct bicycle routes into the city centre. Li, Graham and Liu (2017) investigated the safety effects of these new cycling routes based on panel data from 2007 to 2014. The results show an increase in bicycle traffic on the Cycle Superhighways and an increase in the absolute number of bicycle crashes. However, after controlling for exposure, the results suggest no significant difference in bicycle crash rates between the Cycle Superhighways and the control group. This implies that Cycle Superhighways are not more dangerous or safer than other roads and the increase in bicycle crash numbers on the Cycle Superhighways can be attributed to the increase in bicycle use on those roads.

Although most route choice studies were excluded as they mainly focus on other perspectives than objective safety, two route choice studies included objective safety in their analysis and are worth discussing. Dessing et al. (2016) compared the safety levels of different routes. This study investigated the difference between the shortest and actual route of children during walking and cycling to school. The results show that the actual chosen cycling routes have lower numbers of crashes per kilometre compared to the calculated shortest routes. The authors argue that as children prefer using access roads on their route, it is likely they avoid busy distributors where crashes occur more often. Another route choice study which included crashes in the route choice model used GPS data from a bikeshare system in Arizona, USA (Shah & Cherry, 2021). The results show that cyclists avoid historic crash locations. The authors argue that one reason could be that cyclists are aware of location with a crash history or that cyclists have an increased perceived risk at those locations. Moreover, it seemed that regular cyclists (cyclists with a monthly or annual subscription for the bikeshare system) took an average detour of 1.6 times longer than occasional cyclists (cyclists paying per ride) to avoid historic crash locations. The authors declare that regular cyclists could be more aware of crash locations and may be more aware of suitable detours to avoid such locations compared to occasional cyclists. Furthermore, it may be that cyclists remember dangerous road sections better than non-dangerous road sections. In this way, it may be possible to use crash locations as a proxy for perceived safety.

2.1.3 Cycling safety at the road level

This section is divided over three parts. First, the association between cyclist safety and road sections as well as intersections are discussed. Second, the effects of different types of cycling infrastructure on cyclist safety are described. Third, the impact of transitions and discontinuities in the cycling network on cyclist safety are discussed. Note, depending on the study, physically separated bicycle tracks along a road may also be referred to as cycle tracks.

Road sections and intersections

Studies that have focused on a more microscopic levels (road section or intersection) have found variables such as road category, intersection signalisation type (traffic lights, not signalised, stop signs, priority, etc.), speed limit, etc. to have an effect on cycling safety.

Kaplan, Vavatsoulas and Prato (2014) used crash data to evaluate cycling injury severity in Denmark based on the following infrastructural elements: posted speed limit, presence of cycling facility, road section vs. intersection, and number of lanes. They found that higher speed limits result in a greater probability of higher injury severity for cyclists, presence of a cycling facility decreases the probability of a cyclist fatality, and multi-lane roads (compared to single-lane roads) have a higher probability of severe or fatal crashes for cyclists. Lastly, while most crashes occurred at intersections, crashes at road sections have a higher probability for increased injury severity. This may be a result of annual campaigns aiming at higher vigilance for cyclists at intersections.

Lovelace, Roberts and Kellar (2016) investigated crashes involving cyclists within West Yorkshire, UK. They found that higher speed roads such as collector or arterial roads have a higher risk of cyclist injury, and that most crashes were observed at intersections and roundabouts, while higher injury severity and fatality crashes occur on road sections.

Prati, Pietrantoni and Fraboni (2017) performed a cyclist crash severity prediction study in Italy. Focusing on road type, road signage, and type of road section. They predicted that the probability of having a fatal crash is higher on urban roads with higher motor vehicle speeds compared to lower speed municipal roads. Also, lower crash prediction was found for locations with a road sign. Finally, a higher cyclist crash risk was predicted on road sections compared to intersections and roundabouts.

Sayed (1997) used traffic conflict techniques to evaluate cycling safety. He used type of intersection control, speed limit, and number of lanes as infrastructural variables. He found that at unsignalised intersections, as the traffic volume increased, conflicts were more likely to occur (compared to stop-controlled intersections). He found that higher speed limits increase the chance of a cyclist-vehicle conflict, and that more lanes increase the chance of such conflicts.

Residential roads have lower injury odds than other street types (Aldred et al., 2018). A study done in Beijing showed that only 4% of cyclist fatalities occurred on access roads and the other 96% were on arterials, distributors, and highways (Liu, Shen & Huang, 1995). Similarly, Teschke et al. (2012) performed a risk-analysis study and found that cyclist have a lower crash risk on local roads compared to major streets.

At the intersection level, safety studies generally conclude that intersections pose a higher risk to cycling safety (Osama & Sayed, 2016; Siddiqui, Abdel-Aty & Choi, 2012; SWOV, 2021; Wei & Lovegrove, 2013). Wei and Lovegrove (2013) studied crash data from British Colombia, Canada, and found that intersection density, and arterial-local intersection types increase crash risk. A study done in Beijing showed that 54% of cyclists' fatalities occurred at intersections (Liu, Shen & Huang, 1995). In the Netherlands, in 2020 an identical 54% of cyclists' fatalities occurred at intersections. Within the urban area, this amounted to 60% (SWOV, 2021). Moreover, in the Netherlands, roundabouts are the safest form of intersections for cyclists (Dijkstra, 2014; Wijnen, Weijermars & Bos, 2013). On a roundabout, there are fewer points of conflict and lower motorised traffic speeds compared to a prioritised or especially a signalised intersection (SWOV, 2021).

Schepers et al. (2011) investigated the influence of road characteristics on bicycle-motor vehicle crashes at unsignalised priority intersections. They distinguish two types of crashes: Type I are crashes where the cyclist rides on the priority or distributor road, and collides with a vehicle entering or leaving the side road; and Type II are crashes where the cyclist crosses the priority/distributor road and collides with a vehicle driving on the priority/distributor road. Crashes of the first type occur more often than crashes of the second type. On the contrary, the risk for a cyclist of being involved in a Type II crashes is relatively higher per cyclist than the risk of being involved in a Type I crash. The probability of Type 1 crashes can be reduced by speed-reducing measures for vehicles entering or leaving the distributor road Moreover, the number of crashes is lower at intersections with a bicycle track located between 2 meters and 5 meters away from the main road. When the bicycle track is less than 2 meters away from the main road, the crash probability is similar to the crash probability of bicycle lanes. A study has been identified indicating that turning manoeuvres are unsafe for cyclists. Wijlhuizen, Nabavi Niaki and Dijkstra (2021) used video data and surrogate safety measures to evaluate the safety of left-turning cyclists in The Hague (the Netherlands). They found that providing dedicated crossing and traffic light phase for cyclists making a left turn at an intersection can improve safety by 92%. In relation to this, in Denmark, Kaplan, Vavatsoulas and Prato (2014) found that crashes between left turning cyclists and through vehicles have a 304% higher chance of a cyclist fatality compared to other crash movements. Another approach of left-turns is to investigate left-turns from the perspective of drivers. In Boston, Saeidi Razavi and Furth (2021), have shown that left-turning vehicles at priority intersections pose a risk to cyclists, especially at bidirectional bicycle tracks.

Cycling infrastructure

The safety of different cycling facility types has been compared in literature as well. Teschke et al. (2012) performed a risk-analysis study and found that cyclist have the lowest risk of a crash when riding on a bicycle track compared to no facility. Several studies found that separated bicycle tracks are safer than other cycling facility types. This applies to the combination of road sections and intersections in the Netherlands (Welleman & Dijkstra, 1988). A recent Dutch study, carried out in Amsterdam, showed a positive effect on cycling safety (two times lower crash risk) of separated bicycle tracks compared to non-separated marked bicycle lanes (Van Petegem, Schepers & Wijlhuizen, 2021). In his bachelor's thesis, Beek (2019) found that regardless of type, the presence of any bicycle facility reduces cycling risk by a factor of 4.3. International studies have found that dedicated bicycle tracks along busy streets reduce crash risk and risk of injury by roughly 49% to 90% (Kullgren et al., 2019; Ling et al., 2020; Teschke et al., 2012; Thomas & De Robertis, 2013). A study by Minikel (2012) in the U.S. showed that collision rates are two to eight times lower along bicycle boulevards compared to parallel adjacent arterials. A bicycle boulevard in this study means a traffic calmed side street designated and improved for cyclists where motor vehicle volume and speed are very low. Lusk et al. (2011) found the risk to be 3.5 times lower along dedicated bicycle tracks compared to parallel roads without a bicycle facility.

In addition to literature about the safety of separated bicycle tracks are studies including both unidirectional and bidirectional bicycle tracks. For example, Schepers et al. (2011) found that bidirectional bicycle tracks at unsignalised priority intersections are less safe compared to the unidirectional variant. This was also concluded in a literature review by Thomas and De Robertis (2013) and in a study in Brussels by Vandenbulcke, Thomas and Int Panis (2014). All studies explain the increased risk of bidirectional bicycle tracks by the absence of expecting cyclists from opposite direction by drivers and related visual search strategies at intersections. In relation to these studies, Methorst et al. (2017) hypothesised that turning all unidirectional bicycle tracks into bidirectional bicycle tracks in the Netherlands would improve cyclist safety as this would lead to increased expectations of contra-flow cycling and adapted visual search strategies. However, this hypothesis is rejected as a large share of the separated bicycle tracks is already bidirectional in the Netherlands, and still an increased risk was found for bicycle-motor vehicle crashes at bidirectional bicycle tracks (Methorst et al., 2017).

Transitions and discontinuities

A final important infrastructural element at the road section level are transitions between road sections or discontinuities of cycling infrastructure. This is getting less attention in the literature compared to road sections and intersections. However, there is one study explaining which types of transitions, or discontinuities, can be present in a cycling network. Krizek and Roland (2005) investigated three groups of discontinuities of on-street bicycle lanes in Minneapolis, US. The first group indicates two-directional bicycle lanes located at the left side of the street which end, forcing the cyclist to cross the street to continue cycling on the right side of the road in the same direction. Such locations become extra dangerous when a road with a left-side two-directional bicycle lane intersects with another road with one-directional bicycle lanes on either side of the road. Although two-directional bicycle lanes are not common in the Netherlands, similar situations may occur with two-directional bicycle tracks in the Netherlands. The second group indicates locations where a bicycle lane is disrupted by an intersection and where the bicycle lane dissipated after the intersection. The last group consists of locations where bicycle lanes end under relatively innocent conditions. This group marks transitions from bicycle lanes to mixed traffic conditions. A survey was used to investigate the level of discomfort of these three types of discontinuities. The conclusions were that discontinuities contribute to increased discomfort of cyclists when bicycle lanes end on the left side of the street, when there is parking after the discontinuity, when it leads to increased distance of crossing intersections, or when there is an increased width of the kerb lane.

Similar to the study by Krizek and Roland (2005), Niaki, Saunier and Miranda-Moreno (2018) investigated cycling behaviour at cycling facility discontinuities in Montreal. By analysing video data, it was shown that cyclists increasingly vary in speed, acceleration and deceleration, and choice in manoeuvres at discontinuity locations. This indicates that cyclists with different levels of comfort adjust their speed and movements to pass a discontinuity of the bicycle facility.

In Vandenbulcke, Int Panis and Thomas (2017), it was shown that bicycle crashes, besides some other locations, tend to occur around discontinuities in the cycling network of Brussels, Belgium. Discontinuities are here defined as the end or an interruption over some distance of the bicycle facility, often located at intersections. Similar results were found by Vandenbulcke, Thomas and Int Panis (2014), where the discontinuous character of bicycle lanes at intersections leads to an increased crash risk for cyclists.

2.2 Sustainable Safety

Sustainable Safety is a vision to road safety that was first developed around 1990 (Koornstra et al., 1992) and was updated in 2005 (Wegman & Aarts, 2006) and 2018 (Aarts & Dijkstra, 2018). The five key principles of Sustainable Safety are presented in *Section 2.2.1*. *Section 2.2.2* subsequently focuses on the principles *Functionality* and *(Bio)mechanics* in relation to cyclist safety on a route level. *Section 2.2.3* discusses Sustainable Safety in relation to safe routes.

2.2.1 Sustainable Safety principles

Table 2.1 shows the five current principles and their descriptions, where the first three are the design principles and the last two are the organisation principles.

Table 2.1. The five Sustainable Safety principles (SWOV, 2018)

Sustainable Safety principle	Description
Functionality	Road sections and intersections have only one function for all modes of transport (mono-functionality): a traffic flow function or an exchange function. The road network shows a hierarchical and functional structure of these functions.
(Bio)mechanics	Traffic flows and transport modes are compatible with respect to speed, direction, mass, size, and degree of protection. This is supported by the design of the road, the road environment, the vehicle, and, where necessary, additional protective devices. For two-wheeled vehicles, it is important that the road and the road environment contribute to the stability of the rider.
Psychologics	The design of the traffic system is well-aligned with the general competencies and expectations of road users, with senior road users in particular. This means that for them as well as others the information from the traffic system is perceivable, understandable (“self-explaining”), credible, relevant, and feasible. Road users are capable to carry out their traffic task and to adjust their behaviour according to the task demands for safely participating in traffic under the prevailing circumstances. This applies for drivers (skilled and fit for the driving task) as well as non-motorised road users (skilled in dealing with traffic and fit to participate in traffic).
Responsibility	Responsibilities are allocated and institutionally embedded in such a way that they guarantee a maximum road safety result for each road user and optimally integrate with the inherent roles and motives of the parties involved. In principle, road users follow the rules and set a good example for children and teenagers. Thanks to a forgiving traffic system, road users will not be punished for their errors and weaknesses by crashing and sustaining serious injuries.
Learning and innovating	Traffic professionals continually learn how they can improve their policy. The Deming cycle is relevant here: it starts with the development of effective and preventive system innovations based on knowledge of causes of crashes and hazards (Plan). By implementing these innovations (Do), by monitoring their effectiveness (Check) and by making the necessary adjustments (Act), system innovation ultimately results in fewer crashes and casualties.

2.2.2 Sustainable Safety applied to bicycle traffic

Two of the principles in *Table 2.1* need specific attention, as these are especially relevant for the current study. The first principle is Functionality, which implies the hierarchical and functional structure of traffic functions in the road network. The second relevant principle for network indicators for safe cycling routes is (Bio)mechanics. This principle in general means that fast-flowing traffic is separated (physically or in time) from slow moving traffic, from traffic travelling in the opposite direction, from traffic with a considerably different mass or width, from hazardous obstacles, and from vulnerable road users. These principles are mainly focused on protecting vulnerable road users from motorised traffic. However, the principles could be applied to bicycle traffic as well. This is also discussed by Weijermars et al. (2013). This section summarises the main conclusions from that study.

Functionality of bicycle facilities

In Sustainable Safety, the hierarchical and functional structure of traffic functions in the road network are specified in three road categories:

1. Access roads: exchange function on road section and at intersections;
2. Distributor roads: flow function on road section and exchange function at intersections;
3. Through roads: flow function on road section and across intersections.

"Flow" in this sense means that there is no interaction between traffic and the environment, while with "exchange" this interaction appears, for example, as abrupt manoeuvres in residential areas (e.g. entering private properties). As it is not safe to combine the flow and the exchange functions in one road section or intersection, these must be separated. Road functionality in this way is the foundation for a safe design and use of roads (SWOV, 2018).

Weijermars et al. (2013) argued that the functionality principle could also be applied to bicycle traffic. In that case, also for bicycle traffic, two types of facilities could be distinguished, depending on the traffic function of the bicycle traffic (flow or exchange). It may be desired to guide bicycle through-traffic and bicycle exchange traffic over different routes or road types. For example, flowing cyclists may be more dedicated to main routes with bicycle highways for bicycle through-traffic, while exchanging cyclists may be more dedicated to local routes/roads with the exchange function. These local roads allow for more different types of cyclists and have lower average cycling speeds, while bicycle highways are designed to quickly travel large distances without interruptions of intersections (Weijermars et al., 2013). However, the feasibility and desirability of dividing these groups of cyclists still needs more research.

Weijermars et al. (2013) mentioned that also the operationalisation of the functionality principle for bicycle traffic in practice needs more work and probably is not an easy task. One of the challenges in that respect is the alignment of the cycling network with the car network. In order to minimise conflicts with motorised traffic, it is not recommended to guide bicycle flow traffic along distributor roads. This is supported by the findings of Schepers et al. (2011) and Schepers et al. (2013) that are discussed in *Section 2.1*. Where to facilitate bicycle through-traffic depends on the spatial planning of an area, the available space, and the amount of bicycle traffic. For example, existing urban areas may not have enough space available for exclusive bicycle tracks without intersections and it may be desired to have enough connections to a bicycle facility with a flow function. Another issue is whether it is desired that a bicycle facility with a flow function crosses a residential area when it is decided that fast flowing bicycle traffic must be separated from slow bicycle traffic and other road users in the residential area. On the other hand, it is challenging to guide cyclists around residential areas, since it may have a longer detour from the shortest path. A solution may be that a bicycle facility with a flow function crosses a residential area, but is (physically) separated from traffic with an exchange function (Weijermars et al., 2013).

To have a better understanding of road functionality and how to apply this to network indicators and route choice of both car traffic and bicycle traffic, it is necessary to go back to the roots of Sustainable Safety. This is where the functional requirements for the categorisation of roads were developed. These functional requirements are developed to create a sustainable safe road network. *Table 2.2* shows the first four functional requirement in Janssen (1997) as how they are meant for car traffic and the same four functional requirements in Weijermars et al. (2013) as how they are applied on bicycle traffic.

Table 2.2. Functional requirements of the Sustainable Safety principle of 'Functionality' for car traffic and bicycle traffic.

Functional requirement	**Car traffic (Janssen, 1997)**	**Bicycle traffic (Weijermars et al., 2013)**
Minimal part of the route on relatively unsafe roads	As not all roads are equally safe, it is important that the least safe roads occupy the lowest proportion of a route. The road network must be adapted to this, which also achieves that the function and the use of a road comply. Although access roads may have a modest chance of a crash, it does not imply more traffic should follow access roads. On the contrary, this would counter the safety of these roads as the combination of function, design, and use is incorrect. The 'functional' traffic on access roads should be guided as quickly as possible to distributor roads. The distributor roads should serve as quick connectors to through roads. The safety level of through roads should exceed the other two road categories which makes it beneficial to flow traffic over through roads instead of the other roads. This means that the largest part of a route would follow the relatively safest roads.	Relatively unsafe roads for cyclists are roads with high levels of motorised traffic, while the safest roads are found in residential areas since they are generally not used for motor vehicle through-traffic. In this way, there are less conflicts between motor vehicles and cyclists. In addition, this requirement can also be applied on bicycle traffic, as explained above, relating to the separation of bicycle flow traffic and bicycle exchange traffic.
Routes as short as possible	When a road user has to travel a longer distance, the chance of a crash increases; the 'exposure' increases. It is therefore necessary to allow as short as possible routes, which goes for all road users. As this requirement applies on the whole route, the three road categories should satisfy this in proportion for their share in the route.	Similar to motor vehicles, it is important for cyclist safety to minimise the exposure to risks in traffic, resulting in as short as possible routes.
Shortest and safest route must be the same	Road users mostly take the shortest route to their destination. It is therefore important that the road network enables the shortest route to be the safest route. This is equally important for all road users. Moreover, the desire to decrease the trip duration may not result in increased driving speeds. For access roads, this means one should aim for short connections with the next road category, expressed by the travel time/distance criterium. The value of this criterium can be differentiated to the number and the type of connected yards. This is also applicable on distributor roads, but then related to the number of intersections. For route choice, time gain of a distributor road compared to an access road may be an argument. This also applies for through roads compared to distributor roads.	This requirement is a combination of the former two requirements. Cyclists are likely to choose the shortest route (in time and/or distance), possibly with the least number of interruptions like intersections (Broach, Dill & Gliebe, 2012; Menghini et al., 2010). Shortest routes that are not safe enough for cyclists should be made safer.
Avoid search behaviour	The road user must be able to easily find the shortest road to prevent unnecessary driving. Problems with search behaviour vary across the three road functions. In a sustainable safe road network, finding a destination should only be a problem on access roads. In addition, search behaviour may lead to distractions and unsafe manoeuvres like a U-turn.	It is also important for cyclist safety to avoid search behaviour, as search behaviour potentially leads to unsafe situations. A route should therefore easily be found.

There is one additional functional requirement: 'as large as possible residential areas'. However, it is difficult to apply this requirement to bicycle traffic and it may even contradict with the functionality principle for bicycle traffic. In case a distinction would be made between bicycle through-traffic and bicycle exchange traffic, and if it is desired to separate bicycle through-traffic from bicycle exchange traffic and other vulnerable road users, it could be argued that it is not desirable to guide bicycle through-traffic through residential areas. However, routes around large residential areas would result in long routes with high detour factors that are not attractive for bicycle through-traffic. Therefore, it cannot be expected from bicycle through-traffic to avoid riding through these ‘as large as possible residential areas’. Hence, it may be preferred to (physically) separate bicycle through-traffic from exchange traffic in residential areas (Weijermars et al., 2013).

(Bio)mechanics for cyclists

To achieve separation (physically or in time) of fast-flowing traffic from slow moving traffic, from traffic travelling in the opposite direction, from traffic with a considerably different mass or width, from hazardous obstacles, and from vulnerable road users, the road and its environment must be forgiving. This means that the free flow speed is safe for all road users in the event of an incident. *Table 2.3* shows the implementation of safe speed limits. Moreover, road users must be adequately physically protected by the vehicle, by roadside barriers, or by protection devices on the body of the road users. When it is impossible for a transport mode to achieve the speed, mass, size, and road users’ protection criteria that are necessary of a safe outcome, this mode is prohibited from driving on roads with a flow function. These modes of transport require special infrastructure that is designed for traffic with low speed and small size and mass (SWOV, 2018).

Table 2.3. Implementation of safe speed limits (SWOV, 2018).

Safe speed	Potential conflicts and requirements
15 km/h	› Potential conflicts with vulnerable road users in home zones
30 km/h	› Potential conflicts with vulnerable road users on roads, at intersections, including situations with bicycle lanes or advisory bicycle lanes
50 km/h	› No conflicts with vulnerable road users, except with helmet-protected rides of motorised two-wheelers (mopeds in the carriageway) › Potential right-angle conflicts between motor vehicles, potential frontal conflicts between motor vehicles › Stopping sight distance ≥ 47 m
60 km/h	› No conflicts with vulnerable road users › No right-angle conflicts between motor vehicles, potential frontal conflicts between motor vehicles › Obstacles shielded or obstacle-free zone ≥ 2.5 m, (semi-)hard shoulder › Stopping sight distance ≥ 64 m
70 km/h	› No conflicts with vulnerable road users › No right-angle conflicts between motor vehicles, potential frontal conflicts between motor vehicles › Obstacles shielded or obstacle-free zone ≥ 4.5 m, (semi-)hard shoulder › Stopping sight distance ≥ 82 m
80 km/h	› No conflicts with vulnerable road users › No right-angle or frontal conflicts between motor vehicles › Obstacles shielded or obstacle-free zone ≥ 6 m, (semi-)hard shoulder › Stopping sight distance ≥ 105 m
100 km/h	› No conflicts with vulnerable road users › No interactive and frontal conflicts between motor vehicles › Obstacles shielded or obstacle-free zone ≥ 10 m, hard shoulder › Stopping sight distance ≥ 170 m
120 km/h	› No conflicts with vulnerable road users › No interactive and frontal conflicts between motor vehicles › Obstacles shielded or obstacle-free zone ≥ 13 m, hard shoulder › Stopping sight distance ≥ 260 m
130 km/h	› No conflicts with vulnerable road users › No interactive and frontal conflicts between motor vehicles › Obstacles shielded or obstacle-free zone ≥ 14.5 m, hard shoulder › Stopping sight distance ≥ 315 m

Similar to Functionality, Weijermars et al. (2013) applied '(Bio)mechanics' to bicycle traffic. Besides the difference in mass, speed, and direction between motor vehicles and cyclists, bicycles (and other users of cyclist facilities) may also differ in speed, mass, and direction mutually. For example, racing cyclists and e-bicyclers may ride 30 km/h or more while children and senior cyclists may ride 10 to 15 km/h. This also goes for mass, when, for example, heavy (electrified) cargo bicycles use the same bicycle facility as cycling children. The principle of separating heavy and fast bicycle traffic from slower and light bicycle traffic may mean that different types of cyclists use different types of bicycle facilities. Different types of cyclists may be separated based on differences in speed and/or mass (Weijermars et al., 2013). This is also related to the Functionality principle and may result in separating fast flowing cyclists, from slower and more vulnerable cyclists. Another way of separation would be to separate electrically assisted bicycle from conventional bicycles as they vary in speed and sometimes also mass. Moreover, as bicycle facilities with a flow function may be realised through residential areas it is desired that pedestrians are clearly separated from cyclists, especially near bicycle facilities with a flow function, as speed and mass also differ between pedestrians and cyclists.

Table 2.4 shows how the functional requirements of (Bio)mechanics is applied on both car traffic (Janssen, 1997) and bicycle traffic (Weijermars et al., 2013).

Table 2.4. Functional requirements of the Sustainable Safety principle of '(Bio)mechanics' for car traffic and bicycle traffic.

Functional requirement	Car traffic (Janssen, 1997)	Bicycle traffic (Weijermars et al., 2013)
Avoid conflicts with oncoming traffic	It is important to eliminate frontal encounters on roads with high speeds, especially on through roads. These conflicts should also be eliminated on distributor roads with relatively high speeds. Low speeds on access roads should prevent frontal conflicts leading to injury.	Frontal conflicts often result in severe injuries. To avoid frontal conflicts between cyclists, it is important that on two-directional bicycle tracks the separation of the directions is clearly marked. Physical safety barriers are undesirable as these are obstacles which may lead to single-bicycle crashes.
Avoid conflicts at intersections and with crossing pedestrians and cyclists	Cross traffic, including turning vehicles, and crossing traffic, in between intersections, lead to a substantial number of crashes with serious injury. Relative speeds may be higher and vehicles provide insufficient protection against lateral conflicts compared to frontal and/or rear—end conflicts. Especially drivers and passengers of two-wheeled vehicles and pedestrians are vulnerable in such conflicts. The chance of having a conflict with cross traffic or crossing traffic should be eliminated on through roads and as low as possible on distributor roads. Access roads should allow for cross traffic and crossing traffic, especially for pedestrians. The chance of having an injury after such conflicts on access roads is minimised by low speeds of all vehicle types.	Lateral conflicts may also lead to severe injuries, especially with conflicts between cyclists and motor vehicles. This requirement is therefore also important for bicycle traffic.
Separate vehicle types	Vehicles on the same carriageway may have varying mass and movement characteristics and provide different levels of protection. A requirement for a sustainable safe road traffic is that it is essential that the different modes of transport must be separated when the vulnerability of a share of the road users is at stake. Besides vulnerability, differences in mass and speed are reasons for this separation. On through roads, speeds are high which leads to strict separation. Distributor roads may have a less strict separation when the chosen functional speed is lower. The driving speed on access roads must be low enough to make separation unnecessary.	This requirement is important for road users that are vulnerable compared to other road users which have a higher mass or speed or differ in direction. Applied on bicycle traffic, it may be desired to not only separate cyclists from motor vehicles, but also separate different types of cyclists and bicycles based on speed (flow vs. exchange; conventional vs. electrically assisted) and mass (cargo vs. racing), and to separate cyclists from pedestrians.

Functional requirement	**Car traffic (Janssen, 1997)**	**Bicycle traffic (Weijermars et al., 2013)**
Reduce speeds on potential conflict points	While on through roads conflicts with oncoming traffic, cross traffic, and crossing traffic are eliminated, on distributor roads there may be situations where separation is impossible or undesired. When this is the case, the driving speed must be reduced to point from which the road users have enough possibilities to observe, react, and to correct. If there is still a conflict, this mostly results in less serious implications. Such reduced speeds are important on roads with motor vehicles, cyclists and pedestrians. Some access roads, for example, living and shopping streets, may also require speed-reducing measures.	Potential conflict points are locations which are not grasped by the former requirements, and which therefore lead to relatively high risks. This also applies on locations where cyclists pass. Implicitly, the speed of the motorised traffic is meant here. However, also the speed of the bicycle traffic should be reduced on potential conflict points.
Avoid obstacles along the carriageway	Obstacles along the carriageway may increase the severity of a crash. A requirement for a sustainable safe road network is therefore the systematic removal of obstacle in the close vicinity of the carriageway. This requirement leads to elimination, relocation, or protection of obstacles and becomes more urgent when the driving speed is higher. The obstacle-free zone must therefore be larger on through roads compared to distributor roads. For access roads this requirement is less urgent.	This requirement applies to bicycle facilities with on-road obstacles, such as pot-holes and bad pavement quality, and situations where cyclists ride off the road. Obstacles on or close to the bicycle facility are a potential risk factor, especially for single-bicycle crashes.

2.2.3 Sustainable Safety at the route level

The safety level of different routes can be compared to each other. This can be done by two different approaches. The first approach considers the general characteristics of an entire route. The second approach assess the safety level of the different elements that are part of the route and compares the aggregated scores for different routes. These two approaches are comparable to the types of studies on network level that are discussed in *Section 2.1*.

Route level approach

To compare the safety of different routes, the functional requirements can be visualised with a route diagram (*Figure 2.1*). This diagram illustrates the Sustainable Safety character of a route by presenting the road categories of a route against the distance. For cars, a route is more sustainable safe when the correct pattern is achieved: a route should as shortly as possible follow the lower road categories (access roads and distributors) to the highest road category (through roads), with the correct transitions between the categories (one category per transition); stay as long as possible on through roads; and with the correct downward transitions and the shortest distance as possible along the lower road categories to the destination (Dijkstra & Drolenga, 2007). Note that this is only a visual representation; to compare routes, a quantitative assessment is necessary to achieve a final Sustainable Safety score for each route. How to assess and compare the Sustainable Safety level of routes is explained in *Section 2.3*.

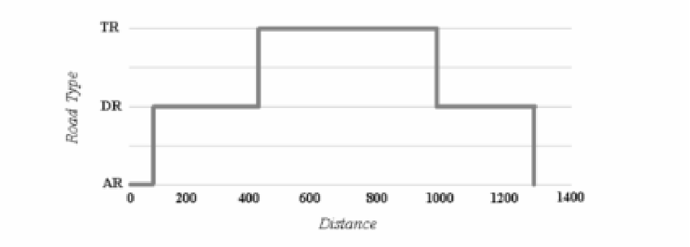


Figure 2.1. Route diagram for a random route (AR = access road, DR = distributor road, TR = through road).

Aggregation of safety level of elements

A second approach is to assess the safety of separate elements of a selected route. To evaluate the safety of a route on the road section level, Safety Performance Indicators (SPI's) can be used. These SPI's help to identify, measure, and monitor the safety level of specific parts of the traffic system leading to safely designed roads (Kennisnetwerk SPV, 2020b). As the design of road infrastructure and cycling infrastructure play an important role in road safety, this helps to prevent the occurrence of crashes and limit the severity when a crash happens. Moreover, well-designed roads ensure that road users automatically follow the traffic rules. Conversely, badly designed roads, or the absence of specific road characteristics, create risks for road safety.

With these SPI's the safety of individual road sections and bicycle facilities which are part of a route can be assessed (Kennisnetwerk SPV, 2020b). This leads to an SPI score per route, which can be used to compare the safety of routes that are part of one OD-pair. Another purpose of the SPI's is to evaluate the safety of the total network, which is related to the network level explained in *Section 1.1*. However, this way of using SPI's is beyond the scope of this study as the focus is on routes rather than the total road network.

2.3 Route safety indicators for cars

A study by Dijkstra (2011) used the Sustainable Safety criteria to develop network safety indicators for car routes. These are explained in the current subsection. From a safe route choice perspective, it is required that, for motor vehicles, the safest route coincides with the fastest route. This requirement should be complemented with another requirement in order to prevent that traffic will drive only/mainly through residential areas because these roads are very safe. Residential areas are not meant to be used by through-traffic and the major part of a route should be on through roads (see *Section 2.2*). To come to such a route choice, the resistance of taking a route through a residential area must be larger than taking a route along through roads and distributor roads (Dijkstra, 2011).

For every route, design features can be compared to design requirements as stated in the Sustainable Safety concept (*Section 2.2*). These are functional requirements which may be applied on the route level. To assess if the shortest and safest route coincide, detailed safety requirements were developed. These safety criteria are to be used on all possible routes in one origin-destination pair (OD-pair) and to compare the level of safety of these routes.

In his thesis, Dijkstra (2011) used nine criteria to assess the safety of car routes. These criteria are based on general knowledge about road safety risks. To visualise the nine criteria, route diagrams are created, which are a visualisation of the Sustainable Safety character of a route. Moreover, to develop a route score, the nine criteria are all quantitative and presented as the lower a score for a criterion, the better for road safety. However, it is beyond the scope of this study to give a detailed representation of the mathematical background of these criteria. Please refer to Chapter 6 in Dijkstra (2011) for a more thorough description of the nine route criteria. See below for a concise description of the nine route criteria and subsequent route diagrams:

1. Number of transitions between road categories must be limited: A transition means moving between road categories, for example switching from an access road to a distributor road. The number of these transitions should not exceed the number of road categories in the network.

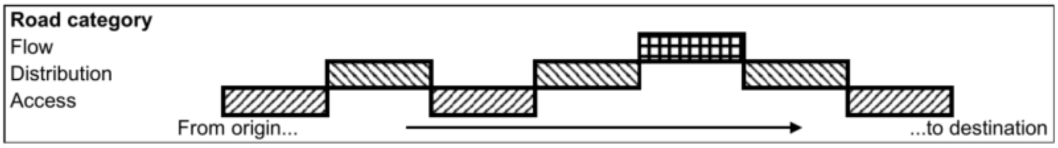


Figure 2.2a. Route diagram with too many transitions (flow = through).

2. Nature of transition is correct (not more than one step at a time): A road user may not skip a road category, meaning that a road user cannot switch from an access road to a through road and the other way around. In between should be a distributor road, making the upward and downward transitions correct. Upward means a transition to higher road category, while downward means a transition to a lower road category.

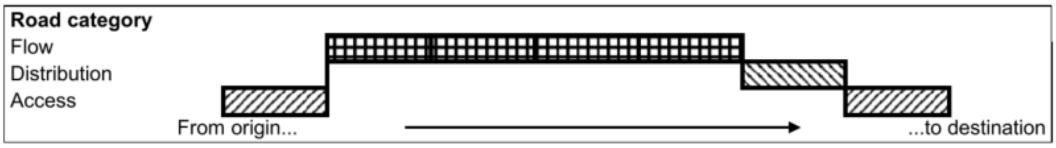


Figure 2.2b. Route diagram showing an incorrect transition, from access road to through (flow) road.

3. As few missing road categories as possible: The number of road categories in a route should be equal to the number of road categories in a network.

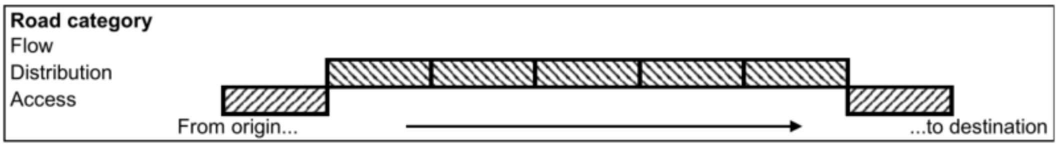


Figure 2.2c. Route diagram with a missing road category.

4. Proportion (in length) of access roads as low as possible: As the amount of through-traffic should be as low as possible on access roads, the proportion of a route on access routes should be limited.

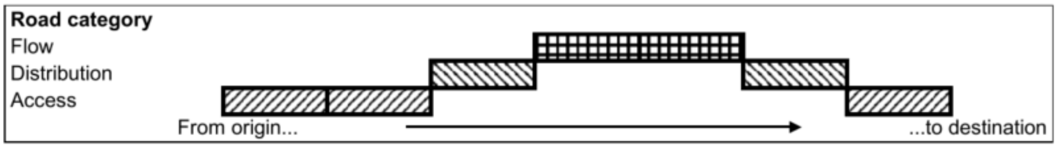


Figure 2.2d. Route diagram showing a relatively high proportion of access roads.

5. Proportion (in length) of distributor roads as low as possible: As distributor roads have the highest crash risk, the proportion of these roads in a route should be as low as possible.

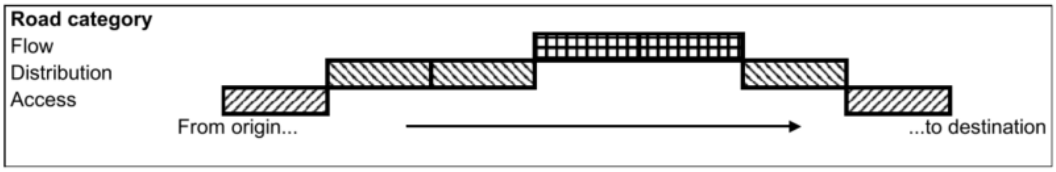


Figure 2.2e. Route diagram showing a relatively high proportion of distributor roads.

6. Travel distance: The lower the distance of a route, the less risk a road user is exposed to.

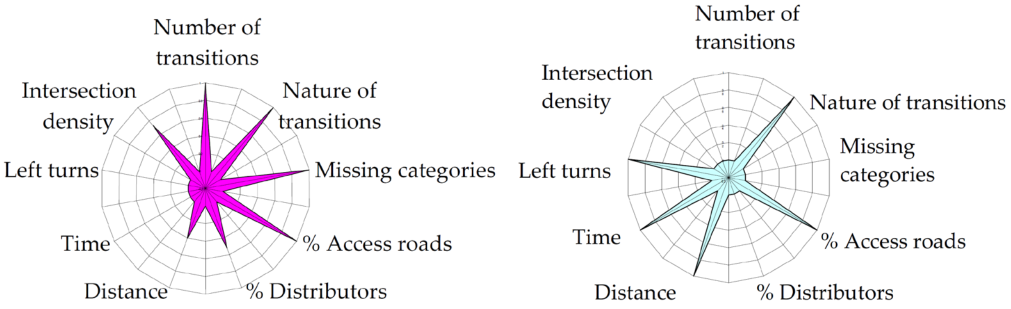
7. Travel time: Similar as for travel distance.

8. As few turnings as possible across oncoming traffic: Left turns at intersections are known to be a risky manoeuvre. They should therefore be as low as possible in a route.

9. Low junction density on distributor roads: The number of intersections on a route should be limited as they are seen as risky locations. This criterion predominantly measures disruptions on the distributor roads in a route.

The first five criteria are closely related to each other and should therefore be used together to assess the Sustainable Safety of a route. The criteria are used to compare routes between an OD-pair with a Sustainable Safety Score. To visually compare the safety of different routes, route stars can be created. The longer a point of the star, the better this route scores on this criterion compared to the other possible routes, meaning that the more complete a star is, the more sustainable safe a route is. *Figure 2.3* is included as an example of route stars from two different routes. The purple star scores best on the first five criteria, the Sustainable Safety criteria, while the green star scores better on the other criteria. However, as the purple star is more complete, this route better meets the requirements of a sustainable safe route. The safety scores of the different routes related to one OD-pair together with the distribution of traffic over these routes are used to calculate the safety level of an OD-pair (Dijkstra, 2011).

Figure 2.3. Route stars of two different routes (Dijkstra, 2011).



In the calculation of the Sustainable Safety Level of an OD-pair, it is important to also include the safety level of routes that are not selected based on the nine criteria, as traffic may still choose one of these routes. Please note that the design of the road sections and intersections that are part of the routes are considered as given factors and not taken into account in these route stars. Instead, the route star focuses on a better understanding of potential safety gains by influencing the route choice of cars (Dijkstra, 2011).

The network indicators discussed in this section are meant for car traffic. In the next section (*Section 2.4*) these indicators are translated to bicycle traffic.

2.4 Synergy: indicators for the safety of cycling routes

Sections 2.1-2.3 have shown which characteristics of routes can be beneficial for cyclist safety and which are not, and how a safe route for cars should look. In this section, this information is combined to create indicators to compare the safety level of different routes for cyclists.

2.4.1 Identified indicators

Section 2.3 discussed the method proposed by Dijkstra (2011) to apply the Sustainable Safety principles on the route level. The functional requirements of Sustainable Safety and general knowledge about road safety risks were combined into nine criteria to assess the safety of routes for motor vehicles. This results in a safety score for every possible route between an OD-pair, which shows the Sustainable Safety character of these routes. While some of these nine criteria may also apply to the safety of cycling routes, others are unapplicable and one can think of the creation of new criteria specifically for cyclist safety. Based on the literature review and the application of the functional requirements and principles of Sustainable Safety on bicycle traffic, the following indicators are proposed to assess the safety of cycling routes in a network:

1. Travel distance as short as possible: The lower the distance of a route, the less risk a cyclist is exposed to.
2. Travel time as short as possible: Similar to travel distance.
3. Low intersection density, especially concerning intersections with distributor roads: The number of intersections on a route should be limited as they are seen as potential conflict points, especially for cyclists. Especially (at-grade) intersections with distributor roads should be avoided as much as possible as they are the least safe for cyclists. Moreover, when two routes are equally safe based on other requirements, the following order of intersection types with distributor roads should be followed in order to choose the safest route:
   3a. *Roundabouts* are preferred over regular priority intersections and intersections with traffic lights.
   3b. *Priority intersections* are preferred over intersections with traffic lights.
   3c. *Signalised intersections* are the least preferred.
   This indicator is justified by the literature on the unsafety of intersections and safety of roundabouts amongst intersection types (Dijkstra, 2014; Liu, Shen & Huang, 1995; Osama & Sayed, 2016; Schepers et al., 2011; Siddiqui, Abdel-Aty & Choi, 2012; SWOV, 2021; Wei & Lovegrove, 2013; Wijnen, Weijermars & Bos, 2013).
4. Wherever possible, cyclists should follow exclusive bicycle tracks: Exclusive bicycle tracks are only accessible for cyclists. This makes them safer compared to roads shared with motor vehicles (SWOV, 2018).
5. Wherever possible, the use of 50km/h distributor roads without separate bicycle tracks should be avoided: When speeds are higher than 30km/h, conflicts between motorised traffic and cyclists should be prevented. Therefore, roads with a 50 km/h speed limit or higher should have a separated bicycle track. This is justified by literature on the safety of bicycle tracks as presented in *Section 2.1* (Kullgren et al., 2019; Ling et al., 2020; Minikel, 2012; Teschke et al., 2012; Thomas & De Robertis, 2013; Van Petegem, Schepers & Wijlhuizen, 2021; Welleman & Dijkstra, 1988).
6. As few left-turns as possible: Left-turns at intersections are known to be a risky manoeuvre for cyclists. They should therefore be as limited as possible in a route. This is supported by literature presented in *Section 2.1* (Kaplan, Vavatsoulas & Prato, 2014; Wijlhuizen, Nabavi Niaki & Dijkstra, 2021).
7. As few transitions and discontinuities as possible: Transitions between and discontinuities of cycling infrastructure lead to increased risk of having a crash and result in increased levels of discomfort for the cyclist (Krizek & Roland, 2005; Niaki, Saunier & Miranda-Moreno, 2018; Vandenbulcke, Int Panis & Thomas, 2017; Vandenbulcke, Thomas & Int Panis, 2014). Transitions and discontinuities should therefore be avoided as much as possible.

2.4.2 Separating bicycle through-traffic?

Besides the need to protect cyclists from motor vehicles, it may also be desired to protect vulnerable road users from large volumes of fast-flowing bicycle through-traffic and other potential users of bicycle facilities, like the upcoming Light Electric Vehicles (LEVs). Vulnerable road users in this respect includes pedestrians and vulnerable cyclists (children and older cyclists). This is related to the (Bio)mechanics principle of Sustainable Safety as applied to bicycle traffic. Vulnerable road users should be protected against high volumes of cyclists, high speed cyclists, and heavier bicycles (Weijermars et al., 2013). An additional indicator dealing with this issue is:

8. Wherever possible, fast flowing and possibly heavy (high-weight) bicycle through-traffic should be separated from ‘residents’ and vulnerable bicycle traffic: This additional indicator aims to minimise serious conflicts between the most vulnerable road users (playing children, children on bicycles, seniors on bicycles) and potentially high speed and/or heavy (high weight) bicycles (and LEVs). The rationale behind it is that bicycle through-traffic is expected, on average, to cycle at higher speed and is expected, on average, to be heavier than ‘local

cycling traffic', for example due to a higher share of e-bikes. Moreover, cycling volumes can be quite high on important OD-relations and ideally high cycling volumes should not be combined with a 'residential' function. Therefore, ideally, there should be a main corridor, preferably an exclusive bicycle track, dedicated to high speed and potentially heavy bicycle 'flow' traffic. More vulnerable cyclists like children and seniors are expected to mainly use cycling facilities in residential areas that are not (primarily) meant for cycling through-traffic, especially during peak hours with high cycling volumes. When it is impossible to separate high-speed and potentially heavy bicycle through-traffic from more vulnerable road users, the provided bicycle facilities should be designed to allow for safe mixing of traffic types.

Unfortunately, research related to this indicator is very limited, which makes it difficult to present evidence for this indicator. However, the suggested indicator is in line with suggestions from other parties.

The *Fietsberaad* has some requirements for the cycling network which hint at separating different types of cyclists. They argue that an extensive, connected cycling network should be provided, which is built up based on different functions of routes. This would allow to realise different routes for different types of cyclists. A general principle would be to have a main cycling network on which most of the cycling trips are travelled (Fietsberaad, 2021).

Also the Dutch Cyclists' Union pleas for more diversity within the cycling network (Bakker et al., 2012). In their vision for 2040, the Dutch Cyclists' Union presents the following three levels in the cycling network (Bot et al., 2019):

1. an '8-80'-network, which is suitable for vulnerable cyclists and includes separated bicycle tracks on busy and '30 km/h'-routes;
2. a main cycling network, which is suitable for all types of cyclists, which can cope with peak hours, and which, to a minimum, satisfies all CROW-requirements;
3. a Cycling Family-network, which is a new network, suitable for the safe flowing of fast and heavy cyclists through an urban area.

Although both visions support the suggested indicator, neither the *Fietsberaad* nor the Dutch Cyclists' Union is able to support their vision with studies showing evidence for their ideas. In line with this, the *Fietsberaad* states that it is necessary to do more research to the feasibility and desirability of implementing different routes for different types of cyclists (Fietsberaad, 2021).

Besides the lack of evidence, there are some complications in operationalising the proposed indicator. Firstly, it needs a clear definition of what bicycle through-traffic exactly means. A possible definition could be that bicycle through-traffic comprises all bicycle traffic that only crosses a neighbourhood on their way to a destination elsewhere. Other than that, one can think of bicycle through-traffic solely being commuters during peak hours. Another option is to make a distinction which is mainly based on speed and mass.

Secondly, it can be complicated to implement a connected network of bicycle tracks exclusively for bicycle through-traffic due to limited available space in urban areas. It might be possible to realise this in newly developed neighbourhoods. Moreover, there are some examples of cities where such network is (partly) realised on the existing cycling network. Utrecht, for example, is already realising the so-called cycling flow routes for cyclists who want to avoid busy routes and too many stops during their route (Degenkamp, Kwantes & Zijp, 2016). These routes are also connected to regional routes outside the urban area. In addition, these routes help to distribute large flows of cyclists over different routes to reduce the flow size on busy cycling routes.

Thirdly, another issue is that cyclists must be triggered to detour from their original route to another, possibly longer route. It is shown in both revealed preference studies with GPS data as well as stated preference studies that commuters, probably the largest group of cyclists in bicycle through-traffic, and cyclists in general want to optimise their route to find the shortest path to their destination and have a strong preference for the most direct route (Bernardi, La Paix Puello & Geurs, 2018; Caulfield, Brick & McCarthy, 2012; Skov-Petersen et al., 2018; Ton et al., 2017). Nevertheless, several studies show that cyclists are willing to take a detour when this increases the level of comfort of their route. For example, it is shown that the number of intersections negatively affects route choice of cyclists. Thus, cyclists are taking a detour to avoid high numbers of intersections (Skov-Petersen et al., 2018; Ton et al., 2017; Vedel, Jacobsen & Skov-Petersen, 2017). Moreover, both revealed and stated preference studies from Copenhagen, Denmark found that cyclists prefer to have exclusive bicycle tracks and separated bicycle tracks on their route and are willing to take a detour from other types of roads (Skov-Petersen et al., 2018; Vedel, Jacobsen & Skov-Petersen, 2017). Lastly, studies from Denmark and Norway show that implementing new bicycle infrastructure stimulates cyclists to adapt their route (Pritchard, Bucher & Frøyen, 2019; Skov-Petersen et al., 2017). Although the majority seemed to be cyclists choosing an alternative route, the studies had difficulties to conclude whether the increased cyclist volumes on the new infrastructure were cyclists actually taking a detour or were new cyclists shifted from other transport modes. This could serve as evidence for the fact that it would be possible to guide cyclists over different routes when this increases their comfort. Note that these factors may be location specific. Cyclists in Amsterdam, for example, have a stronger preference for a shorter route than less intersections during the peak hours (Ton et al., 2017). Moreover, in the same study it was shown that having separated bicycle tracks on a route does not play a role in cyclists' route choice (Ton et al., 2017). This may be related to the quality of the Dutch cycling infrastructure and the different method of creating a choice set compared to other route choice literature.

3 Application of safe cycling indicators

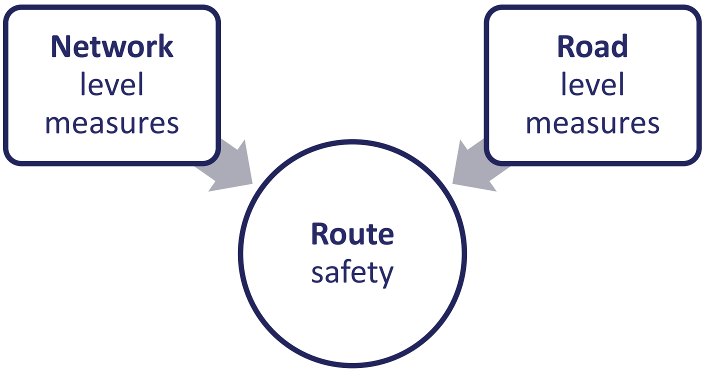
***Chapter 2* presented eight indicators for safe cycling routes. This chapter aims to further specify these indicators with a more practical discussion of the implications for policymakers when tasked with improving cycling network safety.**

After an introduction to the different scales at which road authorities can approach safe cycling routes, *Section 3.2* discusses the roles of different types of infrastructure in the cycling network. *Section 3.3* provides a practical example of how the cycling route indicators can be used to assess network safety. In *Section 3.4*, important road level measures relating to cyclist safety are briefly summarised. *Section 3.5* provides a practical example of the application of the indicators for a number of OD-relations in the city of Utrecht. The chapter is concluded with a discussion of limitations of the application of the safe cycling indicators (*Section 3.6*).

3.1 Introduction

For road authorities, route safety can be addressed with measures taken at different scales (see *Figure 3.1*). A **network-level** perspective is required for larger-scale interventions to change the network structure and ensure that the types of infrastructure match their function in the network. At the **road level**, the focus lies on the redesign of a specific road section/intersection /transition to ensure that the infrastructure satisfies guidelines for safe road design. At the **route level**, the most attractive and popular routes chosen by travelers in the network should also be as safe as possible for both the traveler and other road users. These three levels are, of course, highly interrelated; safe routes are only available if the road sections, intersections, and road transitions they are composed of are also safely designed. At the same time, safe route options will only be chosen if the safest types of infrastructure are available and well-placed within the network. As routes remain the choices of travelers given the infrastructure available to them (and many other personal/situational factors), for road authorities the route level can mainly be influenced indirectly by measures taken at the road or network level. Nevertheless, measures at the road and especially network level can be taken with safe routing in mind.

Figure 3.1.Two scales of measures which road authorities can take to improve route safety



As discussed earlier in *Section 2.1*, much of the research to this day has focused on improving cycling safety using road-level measures, such as adding a separated bicycle track on an existing road. The most relevant road-level characteristics for safe cycling roads and routes, operationalised into "Safety Performance Indicators" (SPIs), are summarised in *Section 3.4*.

Regardless of whether an individual element in the road network is safely designed or not, however, the network may contain alternative routes with different levels of safety. For this reason, the present discussion focuses primarily on measures which can be taken at the network level. In *Section 2.4*, eight indicators were identified which can influence the safety of cycling routes. These indicators involve the preference for certain types of infrastructure, the avoidance of intersections and left-turns, minimizing trip length and separating bicycle flow-traffic from other forms of traffic. The rest of this chapter focuses on a network-oriented perspective for improving bicycle route safety in order to answer the question: How can the safe cycling route indicators be applied at the network level to improve cycling safety?

3.2 Network level application of safe cycling indicators

The safe cycling route indicators outlined in *Section 2.4* can be used to compare the safety of different routes and identify locations in the network where route safety can be improved. Building safe route options, however, only adds to cyclist safety if the safe routes are actually chosen by cyclists. It is therefore important to consider travel demands between different areas in the network as well as cyclists' route preferences (e.g. travel time, environment, pavement) such that the safest routes are also most often chosen. We propose three primary steps in order to apply the safe route indicators at the network level:

1. **Network analysis**
   Identifying bicycle routes of interest between important OD-pairs in network
   - → Between which origins and destinations in the network are the largest travel demands?
   - → Which route options exist between these important origin-destination pairs?
   - → Which routes currently have the highest bicycle traffic volumes?
   - → Which alternative routes exist to the identified routes?
   - → Which other routes may be of interest for other reasons, e.g. known deficiencies, complaints of citizens?
2. **Route safety assessment**
   Evaluating bicycle routes of interest using safety indicators
   - → How do these routes score in terms of the Safe Route Indicators (2.4.1)?
   - → How do the individual road sections score (Safety Performance Indicators)?
   - → Identify places in the network where safe routes are not available/not used
   - → Identify unsafe 'obstacles' (intersections, detours, transitions) in routes
3. **Upgrade cycling network**
   Selecting measures to improve route safety
   - → Which unsafe routes need to be improved and how? Can this be realised and how?
   - → Which safe routes can be made more attractive to cyclists?
   - → Where can current infrastructure be adapted to better serve its function?
   - → Where are additional links desired to provide safe cycling routes?
   - → Plan changes to network & check based on cyclist route preferences

Network analysis
In order to identify important routes to assess and potentially improve, it is important to first analyse the existing travel demands and network structure. Depending on the scale of the study area and budget available, different approaches to a network analysis may be desirable. A

relatively thorough method of network analysis is a method, developed in Germany and described in detail by Dijkstra (2011), where different sizes of population clusters are linked in order to map the desired connections for an ‘ideal’ network structure. In order to analyse the safety of cycling at the route level, two basic steps are necessary: 1) Identifying important origin-destination pairs; 2) Identifying route options between the origin-destination pairs. Depending on the scale of the network considered, data useful in identifying important origin-destination pairs may include: population centres, employment centres, educational centres and other important destinations in the network (e.g. train stations, shopping centres). Bicycle traffic volume data, either observed or predicted in a transport model, may also be helpful in identifying large traffic demands and popular routes within the network.

An implicit assumption in this approach to network analysis is that traffic volumes may be used in order to help prioritise origin-destination pairs and routes to improve within the network. Research indeed suggests that higher bicycle traffic volumes do, typically, result in a higher number of crashes although with a non-linear relationship (Elvik, 2009; Uijtdewilligen et al., 2022; Wegman, Zhang & Dijkstra, 2012). In addition to routes with high bicycle volumes, there might be additional routes of special interest to policy makers, for example routes that may be relevant with regards to future area developments (e.g. housing projects) or routes that are known to be incomplete or perceived to be unsafe.

For each of the selected routes between a certain origin and destination, multiple route alternatives should be explored (in so far as they are present in the network). Route alternatives are a set of unique options to travel between a certain origin and destination in the network. For example, a route following distributor roads may be frequently chosen, but another route along access roads may be able to provide a safe alternative with some improvements. The safe route indicators can be used in the next step to compare route alternatives with each other.

Route safety assessment

Once the routes of interest are identified, the safe cycling route indicators discussed in *Section 2.4* can provide a framework to compare and evaluate different routes based on their safety. Similar to the study of Dijkstra (2011) explained in *Section 2.3*, route alternatives between a given origin and destination can be scored on the first seven indicators and compared with each other, for example using a route star. While it may occur that one route scores much better over its alternatives, each route will likely have mixed safety levels across the indicators. The goal of the indicators is not to provide a precise score in order to rank routes, at least not without further research. Rather, for road authorities the indicators can be used to identify safety concerns along routes which can be improved and routes for which a safer alternative should be provided/made more attractive.

An additional approach is to score the routes based on the road-level characteristics laid out in the Safety Performance Indicators (also see *Section 3.4*). The Safety Performance Indicators can be used to identify particularly unsafe sections of a route, or aggregated to the route-level in order to compare route alternatives. Like the safe route indicators, the goal at the route and network level is to identify routes which should be improved or for which a more attractive alternative should be provided.

Upgrade network

Based on the network analysis and route safety assessment, the completeness and safety of the cycling network can be evaluated in order to choose routes to improve. Routes may be identified where high volumes of bicycle traffic choose a relatively unsafe route due to either the absence of a safe alternative or other cyclist preferences (e.g. shorter travel time, more comfortable pavement). Even where bicycle traffic volumes are lower, particularly unsafe portions of the network may be identified where large safety improvements can be made. Depending on the network structure, observed travel patterns, and the problems identified with a route's safety, different types of measures may be considered:

- Make existing route safer
- Make already safer route more attractive
- Create new route alternatives

What counts as a safe route, however, possibly also depends on the intended functionality of route sections for cyclists. Elaborating on the eighth indicator discussed in *Chapter 2*, one could argue that ideally, safe route options should exist in the network to serve both faster-moving/flow cyclists, as well as alternative options to serve slower-moving/more vulnerable/exchange cyclists. Before redesigning or adding links in the network, therefore, it is important to consider which routes are intended to primarily serve relatively high-speed and possibly heavy cyclist through-traffic, and which routes are suitable for more local cyclists travelling at lower speeds. The roles of different types of cycling facilities in serving these different functions is discussed further in *Section 3.3.1*.

3.3 Network level measures

Once the network has been analysed and evaluated based on bicycle route safety, road authorities can consider a number of measures to reduce cyclists' exposure to safety risks. As mentioned in the previous section, this may involve adding new safer routes to the network, changing existing routes to make them safer, or making a safer route more attractive to cyclists such that it is chosen more often. In order to create safe routes, network-level measures can be taken which:

1. Ensure infrastructure types match their function in the network, for example:
    - Change infrastructure type to match functional role for cyclists in the network
    - Change road function/infrastructure type for motor vehicles
    - Build new infrastructure types which match intended function in the network
2. Reduce conflict points and exposure, for example:
    - Avoid or grade-separate intersections
    - Change traffic lights to roundabouts where grade separation is not possible
    - Avoid transitions which require interacting with motorised traffic (e.g. two-way to one-way bicycle track)
    - Avoid left turns on routes
    - Minimise route length and times to minimise exposure to safety risks (e.g. add shortcuts to avoid detours)

The measures relating to these two groups of measures are discussed in more detail in *Sections 3.3.1* and *3.3.2*. While less directly related to safety, when adding new routes to the network and/or encouraging different route choice behaviour it is important to consider the attractiveness of the route for cyclists such that the safest routes in the network are also most often chosen. Therefore, a last category of measures is distinguished relating to route attractiveness (*Section 3.3.3*).

3.3.1 Function of different cycling facilities in the network

An urban network is comprised of roads with different functions, speeds, designs, and traffic volumes. For motor vehicles, roads in the network generally follow a hierarchy, from low-speed/low-volume access roads at the beginning and end of journeys which lead to higher speed and higher volume distributor and through-roads to cover the most distance. Just like for motor vehicles, a safe cycling network should be designed in such a way that cyclists are led to choosing the safest route alternatives. However, as bicycle route safety is associated with low motorised traffic speeds and volumes, it is not desirable that the cycling network simply runs parallel to the motor vehicle network, matching its hierarchy. Instead, cycling routes should favour infrastructure types which are proven safer for cyclists. As discussed in *Section 2.1.1*, “unbundling” the cycling network from the motor vehicle network such that the fastest cycling routes primarily follow access roads and avoid (at-grade) intersections with distributor roads is associated with lower crash risks for cyclists (Schepers et al., 2013). It is therefore important to consider which types of infrastructure are most suitable for which roles in the cycling network such that the risks of motor vehicle/cyclist, cyclist/cyclist and pedestrian/cyclist crashes are reduced. It is assumed that single bicycle crashes are mostly influenced by road level infrastructure characteristics, although other road users may also be involved in such crashes even when no collision between road users occurs.

Reducing ‘motor vehicle—cyclist’ crash risk exposure

The first priority at the network & route level for reducing the risk of bicycle crashes resulting in serious injury or death is to reduce the risk of crashes between cyclists and motor vehicles. In order to reduce this risk, bicycle routes should as much as possible avoid intersecting roads with high traffic speeds and high volumes of motorised through-traffic. In between intersections, exclusive bicycle tracks are preferred over access roads or distributor roads, as explained in the safe cycling route indicators (*Section 2.4*). In the absence of exclusive cycling facilities, cycling routes should either follow physically separated bicycle tracks along distributor roads or access roads with low speed limits.

Reducing ‘bicycle—bicycle’ and ‘bicycle—pedestrian’ crash risk exposure

Secondly, the risk of crashes with other cyclists or pedestrians can be reduced. As the differences in speed and mass are lower than with motor vehicles, the risk of serious injury or death in the event of a crash is also expected to be lower based on the (bio)mechanics principle. Thus, the first priority remains a separation of bicycle traffic from high speed motor vehicle traffic. Nevertheless, differences in speed, mass, and function across vulnerable road users exist and may continue to increase with the popularity of e-bicycles, cargo bicycles, speed pedelecs, and more. Therefore, as also discussed in *Section 2.4.2*, it may offer additional safety benefits to provide separate facilities especially for cyclists with a flow function and/or higher speeds in order to limit their interaction with lower-speed cyclists and pedestrians.

Infrastructure types and functions

As shown in *Table 3.1*, different infrastructure types can be oriented towards flow/through or exchange/local bicycle traffic depending on both their road-level design and role in the network. Three main road categories accessible to cyclists are distinguished: exclusive bicycle tracks, access roads, and distributor roads. On access and distributor roads, cycling infrastructure may consist of: a bicycle track, bicycle lane, bicycle street, or be absent (mixed traffic).

Ideally, exclusive bicycle tracks with limited local traffic and few connections or intersections would serve bicycle through-traffic. If it is not feasible to construct an exclusive bicycle track, it may be possible to adapt certain access roads or distributor roads with bicycle tracks to serve bicycle though-traffic. Access roads, depending on their characteristics, can either be adapted to complete the flow network or mainly focus on exchange functions. Bicycle streets, while requiring further research into their safety and ideal characteristics, may be an option to serve flow cyclists on access roads when exclusive bicycle tracks are not feasible. Distributor roads are primarily intended for motorised through-traffic and can potentially serve a function for bicycle through-traffic as well. However, due to the high motorised traffic speeds it is important that physically-separated bicycle tracks are present and intersections are minimised and designed as safely as possible.

Table 3.1. Proposed functions of different cycling facilities in the network

Infrastructure category	Important characteristics	Primary function for motor vehicles	Primary function for cyclists
Exclusive bicycle tracks	› Wide enough to support variety of bicycle types and speeds › High bicycle traffic volume › Low adjacent pedestrian volumes › Few intersections, side-roads › Safe track-side verges › Bidirectional bicycle traffic	n/a	Flow
Access roads: flow	› Potential bicycle streets › Low motorised traffic speeds › Low motorised traffic volumes › Minimal exchange traffic › Few intersections, side roads	Exchange	Flow
Access roads: exchange	› Traffic calming › Lower cycling speeds to protect vulnerable cyclists and pedestrians › Low motorised traffic speeds › Low motorised traffic volumes	Exchange	Exchange
Distributor roads	› Separate bicycle track › Uni- or bidirectional bicycle traffic › Avoid at-grade intersections	Flow	Flow

3.3.2 Reducing conflict points and exposure

Because lateral conflicts with motor vehicles can pose a high safety risk to cyclists, intersections, left turns, and infrastructure transitions which require interacting with motor vehicles should be avoided where possible. As discussed in *Section 2.1.3*, a large share of crashes occur at intersections. Intersections may be avoided by either stimulating/creating alternative cycling routes or by grade-separating bicycle and motor vehicle traffic flows such that these modes do not interact. Grade separation can involve infrastructure such as bicycle tunnels, bicycle bridges, or over/underpasses for motor vehicles.

Particularly intersections with distributor roads and using traffic signals should be avoided where possible. If avoiding or grade-separating an intersection is not a possibility, changing the intersection type to either a roundabout (most preferred) or a priority intersection may be an option, as these are considered to be safer alternatives to signalised intersections (Dijkstra, 2014).

Besides intersections, the presence of either bidirectional or unidirectional bicycle tracks and transitions between the two can influence the amount of interactions between cyclists and motor vehicles. On the one hand, unidirectional bicycle tracks/tracks are found to be safer when crossing motor vehicle traffic (e.g. Schepers et al., 2011). On the other hand, bidirectional bicycle tracks/tracks may help reduce the number of left turns across traffic on a route. Transitions between unidirectional and bidirectional bicycle tracks must also be considered, such that the need to cross traffic to access the cycling infrastructure is avoided as much as possible. Where in the network bidirectional and unidirectional bicycle tracks are most suitable will be context dependent, with the ultimate goal of limiting exposure to and interaction with motor vehicle traffic as much as possible.

Lastly, the shorter a route is the less risk a cyclist is exposed to. Therefore, shorter travel distances and travel times are not only important for route attractiveness but also for safety.

3.3.3 Route attractiveness

When adding route alternatives to the network or improving existing ones, cyclist route preferences should be taken into account. This includes aiming for the safest route option to be equivalent to the fastest route option, and at least within an acceptable margin of travel time deviation if the route is made more attractive in other ways. What is found to be an acceptable additional distance (detour) for different route characteristics varies across different studies. In revealed preference studies which reported average detours, observed bicycle trips were on average 7-15% longer than the shortest possible route (Aultman-Hall, Hall & Baetz, 1997; Bernardi, La Paix Puello & Geurs, 2018; Dessing et al., 2016; Gebhard, 2020; Grond, 2016; Pereira Segadilha & da Penha Sanches, 2014). Besides travel time/distance optimisation, some route characteristics which have been shown in route choice studies to attract cyclists include:

- **Wider** (Schjins, 2018) and **smoother/asphalt-paved tracks** (Gebhard, 2020; Pereira Segadilha & da Penha Sanches, 2014; Stinson & Bhat, 2003; van Overdijk, Van der Waerden & Borgers, 2017);
- Lower adjacent **motorised traffic speeds** (Aultman-Hall, Hall & Baetz, 1997; Caulfield, Brick & McCarthy, 2012; Krizek, 2006; Pereira Segadilha & da Penha Sanches, 2014; Sener, Eluru & Bhat, 2009; Snizek, Sick Nielsen & Skov-Petersen, 2013; Sobhani, Aliabadi & Farooq, 2019; Stinson & Bhat, 2003; van Overdijk, Van der Waerden & Borgers, 2017);
- Lower adjacent **motorised traffic volumes** (Broach, Dill & Gliebe, 2012; Li et al., 2012; Misra & Watkins, 2018; Schjins, 2018; Pereira Segadilha & da Penha Sanches, 2014; Sener, Eluru & Bhat, 2009; Zimmermann, Mai & Frejinger, 2017);
- Absence of **on-street parking** (Snizek, Sick Nielsen & Skov-Petersen, 2013; Stinson & Bhat, 2003; Tilahun, Levinson & Krizek, 2007).

3.4 Road level measures

In addition to the network-level measures described in *Section 3.3*, it remains important to ensure that individual elements in the network—road sections, intersections, and transitions—are designed in a sufficiently safe and forgiving way. In the Netherlands, the Kennisnetwerk SPV has identified specific design criteria called “Safety Performance Indicators” (SPIs) to assess if a road section is designed in a safe way (Kennisnetwerk SPV, 2020b). These indicators are summarised below, first in general regarding safe speed limits, and then more specifically regarding safe bicycle tracks.

3.4.1 SPI’s: Sufficiently safe road infrastructure

Three factors determine if a road is sufficiently safe: the function of the road, the design, and the use (Kennisnetwerk SPV, 2020b). The function of a road can be flow or exchange and determines the road design. It also determines the speed limit, which is highly related with safe infrastructure. The use of the road, which are the types of traffic (slow and fast) and its volumes, determine which conflict types can arise and to what extent. The interaction between these three factors affects the degree of safety of a road.

To determine if a road is sufficiently safe, one has to take the speed limit into account. Based on the speed limit one can determine the sufficiently safe road design in order to prevent that specific conflict types lead to severe crashes (Kennisnetwerk SPV, 2020b). When the actual road design corresponds with the safe road design, the road is sufficiently safe and the speed limit is also the safe speed of that road. When this is not the case, the road design has to be changed or the speed limit has to be adjusted.

Several elements have to be taken into account when deciding the safe speed limit, or to decide on the road design corresponding to the safe speed limit. *Table 3.2* shows these elements for roads inside the urban area. As this study focuses at urban roads, design elements for rural roads are not discussed here. *Table 3.3* subsequently further specifies the requirements for roads with different speed limits (inside urban areas).

Table 3.2. Road characteristics for sufficiently safe urban roads (Kennisnetwerk SPV, 2020b).

Road characteristic	Explanation
No parking on or next to the carriageway	Entering or leaving a parking spot and dooring are dangerous for passing motor vehicles and cyclists.
Physical safety barriers	A physical safety barriers prohibits frontal conflicts.
Crossing facilities at roadway sections	Crossing facilities provide safety to crossing pedestrians and cyclists, only if they are designed well.
No property accesses	Property accesses lead to conflicts between the traffic on the distributor road and the access road. Only property accesses implemented as access roads are sufficiently safe.

Table 3.3. Characteristics of sufficiently safe urban roads (Kennisnetwerk SPV, 2020b).

Speed limit (km/h)	Conflicts with oncoming traffic	Single vehicle conflicts	Conflicts with crossing traffic	Conflicts with parked vehicles	Lateral conflicts between motor vehicles and slow traffic
30	No facility necessary	No facility necessary	Speedbump or plateau	Parking on the carriageway or in parking spaces along the road	Mixing of motor vehicles and slow traffic
50	Marked safety barrier	No facility necessary	Crossing facility and/or connection access road	No parking on or along the road	Slow traffic on bicycle track or service road; mopeds on main carriageway
70	Marked safety barrier		Crossing and property accesses not allowed	No parking on or along the road	Slow traffic on (moped-) bicycle track or service road

3.4.2 SPI’s: Sufficiently safe bicycle tracks

SPI’s are also defined for bicycle tracks, which attract a lot of bicycle traffic and on which one third of all bicycle crashes leading to injury and emergency care occur (Kennisnetwerk SPV, 2020a). As these SPI’s are specific to bicycle tracks, they may not apply in their entirety to other types of infrastructure such as bicycle lanes or bicycle streets. Similar to road infrastructure, a bicycle track can become sufficiently safe as a result of interacting factors. These factors are:

- A cyclist should be able to keep their balance;
- The edge and verge should be forgiving for when a cyclist goes off the bicycle track;
- There should be enough space to safely overtake and pass oncoming cyclists.
- The design principles in *Table 3.4* lead to a sufficiently safe bicycle track to prevent bicycle crashes where no motor vehicle is involved. This is an important group of casualties as nearly half of all severely injured road users in the Netherlands results from bicycle crashes where no motor vehicle is involved (Kennisnetwerk SPV, 2020a).

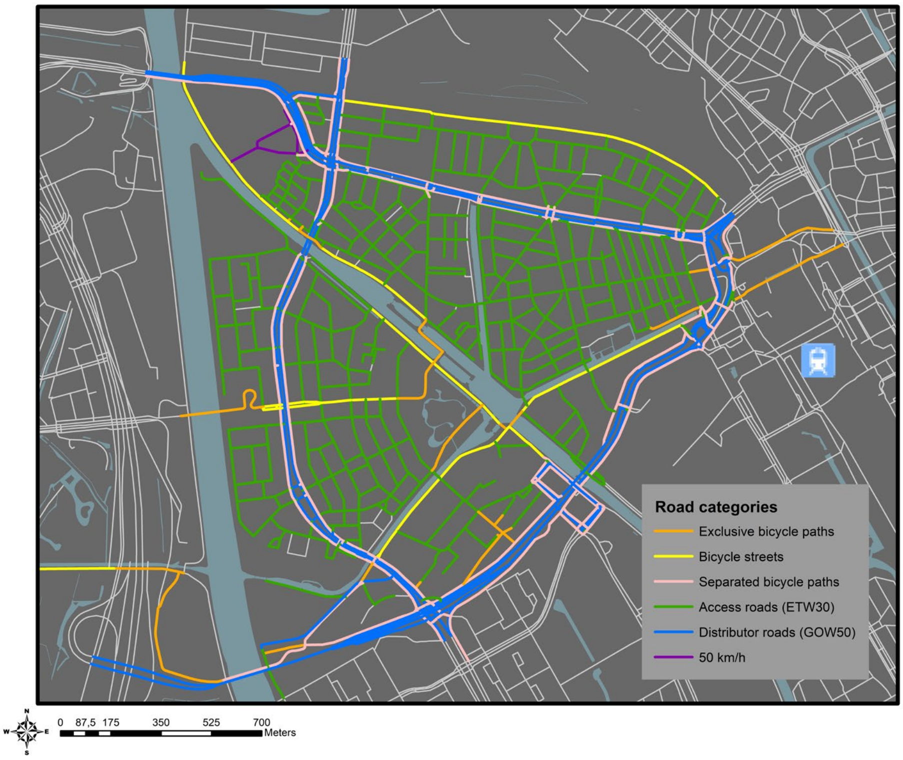
Table 3.4. Design principles for a sufficiently safe bicycle track (Kennisnetwerk SPV, 2020b).

Design principle	**Explanation**
No obstacles	Avoid using poles and other obstacles. A pole can only be placed when the necessity is proven.
Visual guidance	Visual guidance, like edge markings, should be used as a large part of the single-bicycle crashes occur when a cyclist goes off the bicycle track and fall or collides with a kerb.
Wide enough	The width of a bicycle track should allow safe overtaking manoeuvres of cyclists, and possibly also (light) mopeds. There must be enough space to avoid handlebars locking into each other.
Flat, non-slippery, complete, and clean surface	The surface of the bicycle track should be flat, non-slippery, and complete to prevent cyclists going out of balance. This can for example be achieved by using sufficient foundation against damage by tree roots. A bicycle track should also be non-slippery in the winter after snow or ice.
Forgiving edge	Even when the first four design principles are achieved, a cyclists can go off the bicycle track. Therefore, a forgiving edge should be used, for example a chamfered kerb, which prevents a cyclist from collisions and subsequently falling. A cyclist can easily steer back to the bicycle track without falling or slipping away along the kerb.
Forgiving verge	The verge should be wide enough, obstacle free, and rideable. These prevent a cyclist from colliding with an obstacle and falling when entering the verge.

3.5 Example network from Utrecht

This section presents an example of how to use the safe cycling indicators in an existing network. The example network is located in the West of Utrecht and contains the neighbourhoods *Lombok* and *Oog in Al*, presented in *Figure 3.2*. As there are many routes within and across the network, it would be difficult to focus on all possible routes. It is therefore decided to focus on three OD-pairs across the network, all three with two routes to travel to the same destination. These routes result from a network analysis, outlined in *Section 3.5.1*. In *Section 3.5.2*, the safe cycling indicators are used to assess the safety of the routes. To visualise the safety of the three OD-pairs route stars are used. Finally, it is described in *Section 3.5.3* how the different routes could be improved in order to make them safer for cyclists.

Figure 3.2. The example area of the neighbourhoods Lombok and Oog in Al in the West of Utrecht.

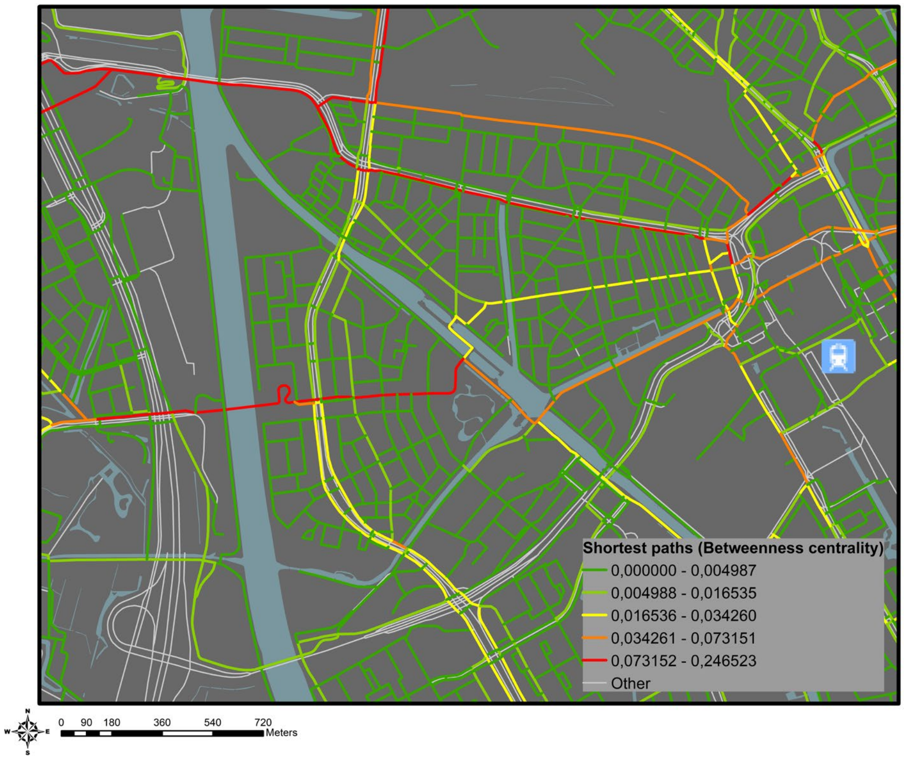


3.5.1 Network analysis

In this section, the steps from the network analysis part presented in *Section 3.2* are used to identify routes of interest in the example area. The origins of these routes are located in the newly developed neighbourhood Leidsche Rijn in the West of Utrecht. Inhabitants of this area need to cross the Amsterdam-Rijnkanaal with one of the three bridges available for cyclists in order to reach the central part of Utrecht. As the Central Station of Utrecht is the largest railway station in the Netherlands and the only intercity station in Utrecht, large flows of cyclists travel to and from this railway station every day. The largest bicycle parking connected to this station is therefore selected as destination of the routes in this study.

To identify routes that are likely to be frequently chosen by cyclists, different data and analysis techniques can be used. In this example, two techniques are illustrated. Firstly, the betweenness centrality of every road section in the network is calculated. This means that the relations between all road sections in the network form the OD-pairs. The technique calculates the shortest paths between every road section in the network. The betweenness centrality of a road section is high when itis passed by many of the shortest routes between every other road section in the network, which results in a network that has a number of roads that serve as the only connection to other roads (Kamel & Sayed, 2020; Zhang et al., 2015). In other words, it shows how important a road section in the cycling network is and how much a network is centred around some individual road sections (Zhang et al., 2015). This would mean that large shares of traffic have to follow the same low number of road sections to move from an origin to a destination. *Figure 3.3* shows the results of calculating the betweenness centrality for the example network of Utrecht. It is expected that the red, orange, and yellow road sections are passed by more cyclists compared to the green road sections. This technique was chosen as it is easily applicable and gives quick results. Note that there may be more advanced techniques to identify shortest routes between origins and destinations, but this was beyond the scope of this study.

Figure 3.3. Results of the betweenness centrality calculation in Utrecht.



Secondly, a different technique is to use collected bicycle volume data. This can, for example, be done by means of GPS devices. An example of such a data set is the Dutch Bicycle Counting Week, which consists of GPS data collected by a sample of 29,000 voluntary cyclists in the Netherlands in 2016[1]. It resulted in a cycling network with weekly counts, although it must be stressed this is only a small part of the actual cycling volumes and that most volunteers cycled in the Randstad area. Therefore, the data may be biased and less applicable in other regions in the Netherlands. *Figure 3.4* shows a representation of the Dutch Bicycle Counting Week in 2016 in the example area. Note that in this year the *Dafne Schippersbrug* (the grey bridge in the middle of the canal in *Figure 3.4*) was still under construction, which has a huge influence on the cycling flows in the selected area. This may also be the reason for the differences between *Figure 3.3* and *Figure 3.4*. It is again important to mention that there are more ways to identify the most important routes between origins and destination. For example, one may choose to use loop detectors on several locations in the network to count the number of cyclists on several road sections, or use traffic volumes predicted using a transportation model if this model has been calibrated to observed bicycle volumes. Another method would be to use questionnaires in the area of interest and ask residents which route they usually take when cycling to a specified destination.

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[1] We are aware of the fact that both in 2015 and 2017 Dutch Bicycle Counting Weeks were held. However, in these years the number of volunteers participating was lower, especially in 2017, which makes these data less representative.

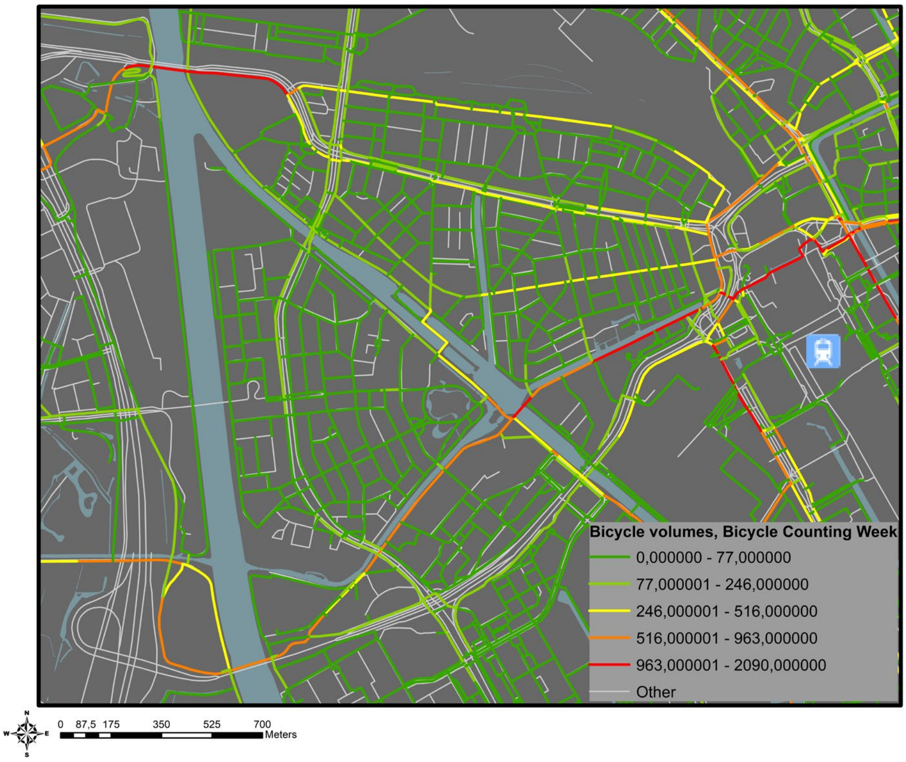
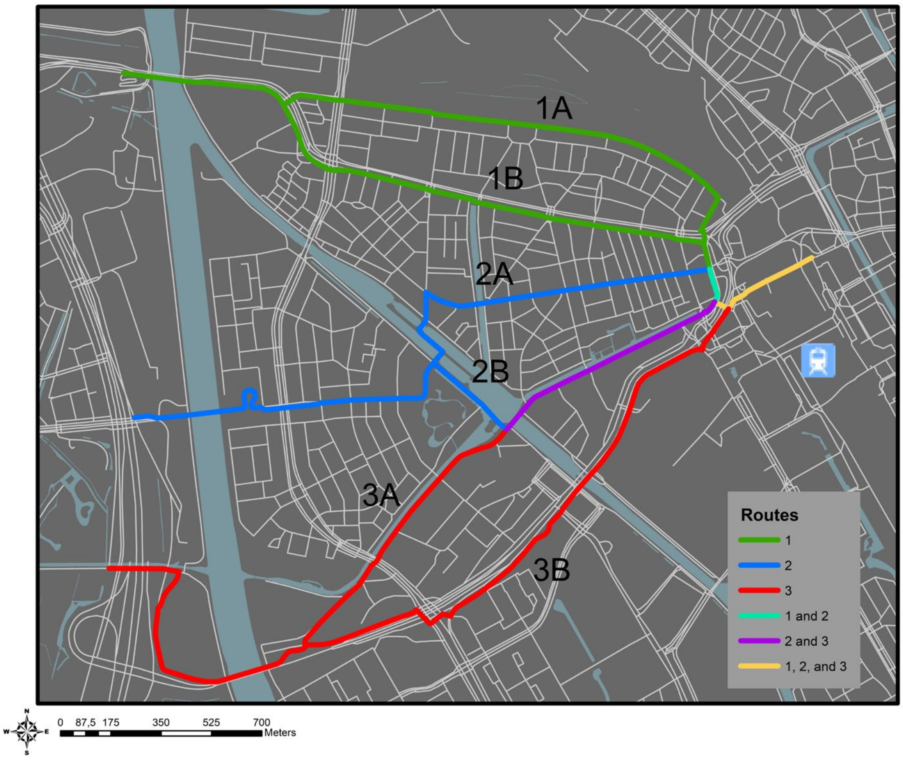


Figure 3.4. Representation of bicycle volumes during the Dutch Bicycle Counting Week 2016 in the example area

The three selected OD-pairs and their route options are presented in *Figure 3.5*. Each of the route options result from a combination of the two techniques outlined above and varies in terms of its cycling infrastructure, the road's function for motor vehicles, travel distance, number of different types of intersections, and more. The first OD-pair, green in *Figure 3.5*, starts at the *Hogeweidebrug* and goes through the Northern part of the example area. Route option 1A follows a bicycle street, while route option 1B follows a distributor road with dedicated bus lanes and separated bicycle tracks. The second OD-pair, blue in *Figure 3.5*, starts at the *Dafne Schippersbrug*, which is exclusively for cyclists, and goes through the middle part of the example area to arrive at the destination. Route option 2A follows access roads with shops on both sides of the street and relatively high motorised traffic volumes, while route option 2B mainly follows bicycle streets. The third OD-pair, red in *Figure 3.5*, starts close to the *De Meernbrug* and goes through the Southern part of the example area. Route option 3A mainly follows bicycle streets, while route option 3B mainly follows four-lane distributor roads with tram tracks and separated bicycle tracks. The selected routes all serve as existing main routes through the example area, although they may vary in popularity. In the next section (*Section 3.5.2*) the safety of the selected routes is assessed based on the indicators presented in *Section 2.4*.

Figure 3.5. Three routes in the example are, which all have two options.



3.5.2 Route safety assessment

To assess the safety of the route options from every OD-pair presented above, the safe cycling indicators are used. As the eighth indicator is only for discussion, only the first seven indicators presented in *Section 2.4* are taken into account. These indicators show which routes are safe and where improvements in the network are desired in order to increase the safety of a route. How the scores of the safe cycling indicators are calculated is outlined in *Appendix B*. The scores are standardised so that the route with the highest (most desirable) score for an indicator has a score of 1 and the route with the lowest score has a score of 0. In the example of Utrecht there are only two route options per OD-pair, so the scores on the items can be 0, 1 or 0,5 (in case both routes obtain the same score on a item). As a result, small differences in for example travel time can lead to large differences in scores between the two routes.

The scores are visualised by means of a route star. The more complete a route star is, the higher the safety of this route is. This would mean that a perfect route scores 1 on every safe cycling indicator and is illustrated by a complete route star.

Total safety score for a route

To come to a total safety score per route, it is first important to determine the weights for each of the safe cycling indicators. In the example of Utrecht, the safe cycling indicators are all weighted equally. This means that each safe cycling indicator has a weighting of 1/9, where 9 is the total number of items on which the routes are scored[2].On the basis of empirical evidence it may be decided to treat one or more indicators as more important than the others. These indicators would then get a higher weight than the less important indicators. The only important criteria is that the sum of all weights always comes to 1 (Dijkstra, 2011). When the weights are determined, the standardised score for each indicator is multiplied by the weight. The sum of these weighted scores is then multiplied by 100%, which leads to the safety score per route (Dijkstra, 2011).

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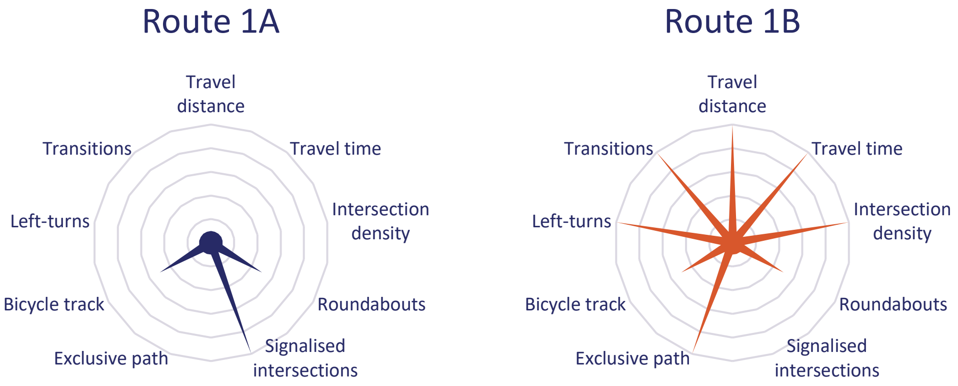
[2] The operationalisation of the eight indicators discussed in Appendix B resulted in ten items on which the routes were scored.

OD-pair 1 (green routes)

In *Figure 3.6*, the route stars of the two routes for OD-pair 1 are presented. Route 1A has a lower number of signalised intersections compared to route 1B. Compared to route 1A, route 1B has a lower travel distance, shorter travel time, lower intersection density, a higher share of exclusive bicycle tracks, a lower number of left-turns, and a lower number of transitions. The scores for the number of roundabouts and separated bicycle tracks on distributor roads are equal for both of the routes. Altogether, this results in the route star for route 1B being more complete than the route star of route 1A. According to the safety scores of the route, route 1B with a safety score of 78% is safer than route 1A with a safety score of 22%.

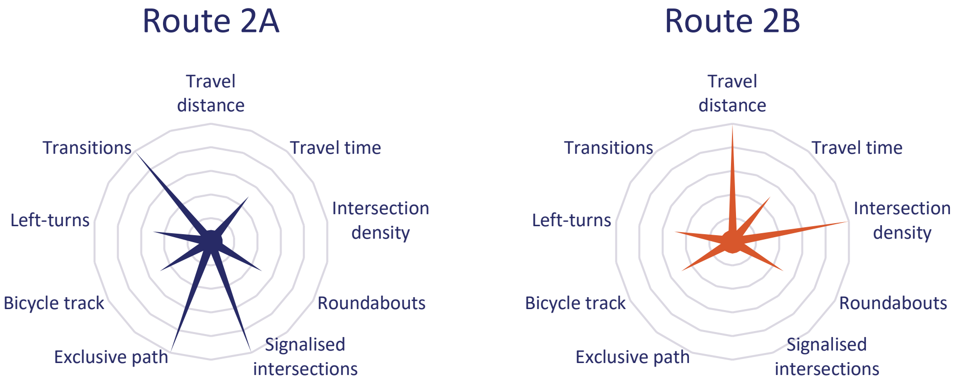
Figure 3.6. Route stars for the two routes of OD-pair 1



OD-pair 2 (blue routes)

In *Figure 3.7*, the route stars of the two routes for OD-pair 2 are presented. Route 2A has a lower number of signalised intersections, a larger share of exclusive bicycle tracks, and a lower number of transitions compared to route 2B. Compared to route 2A, route 2B has a lower travel distance and a lower intersection density. The scores of travel time, the number of roundabouts, the share of separated bicycle tracks on distributor roads, and the number of left-turns are equal for both routes. This makes that the route star of route 2A is more complete than the route star of route 2B. According to the safety scores of the route, route 2A with a safety score of 56% is safer than route 2B with a safety score of 44%.

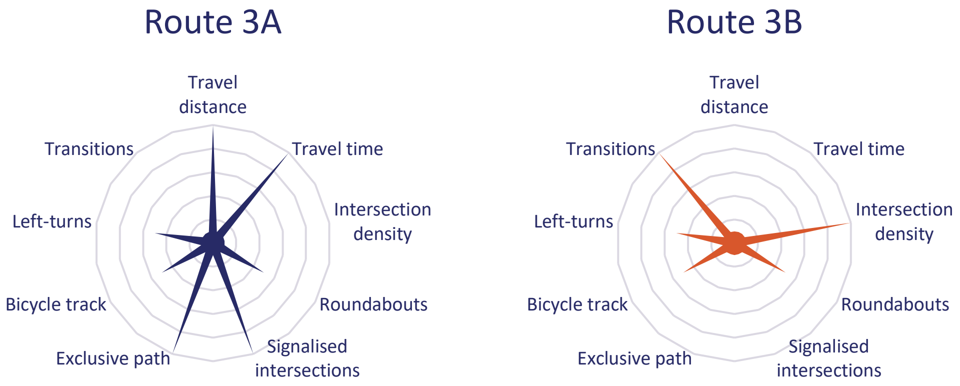
Figure 3.7. Route stars for the two routes of OD-pair 2



OD-pair 3 (red routes)

In *Figure 3.8*, the route stars of the two routes for OD-pair 3 are presented. Route 3A has a lower travel distance, a shorter travel time, a lower number of signalised intersections, and a larger share of exclusive bicycle tracks compared to route 3B. Compared to route 3A, route 3B has a lower intersection density and a lower number of transitions. The scores of the number of roundabouts, the share of separated bicycle tracks on distributor roads, and the number of left-turns are equal for both routes. This makes that the route star of route 3A is more complete than the route star of route 3B. According to the safety scores of the route, route 3A with a safety score of 61% is safer than route 3B with a safety score of 39%.

Figure 3.8. Route stars for the two routes of OD-pair 3



3.5.3 Upgrading the network

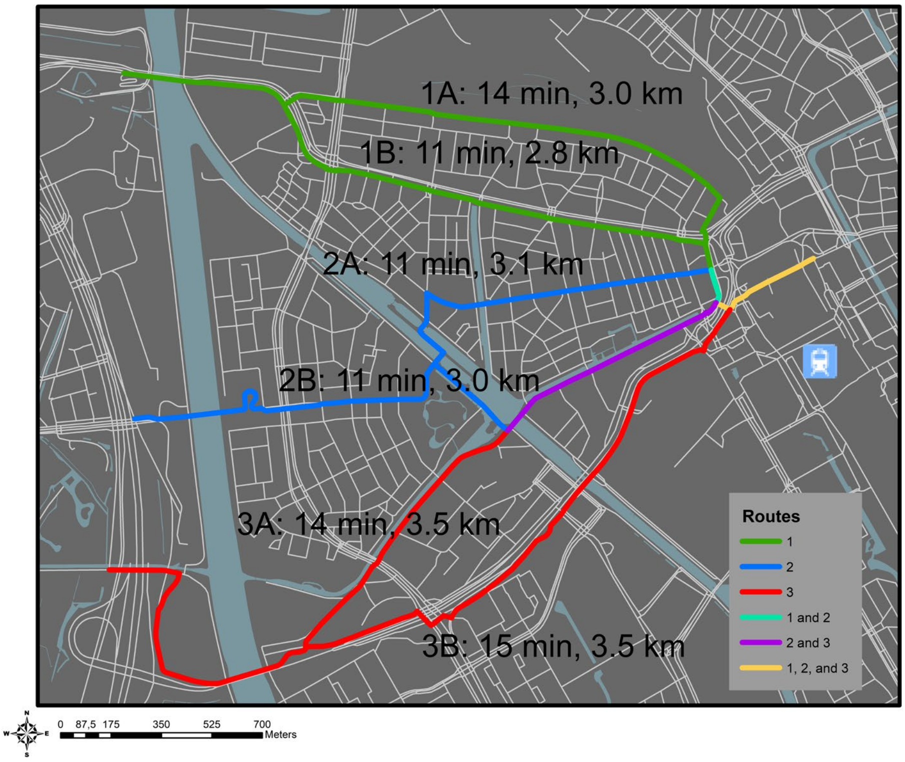
In this section, the safety of the routes is evaluated in more detail and, where possible, improvements are suggested to upgrade the network.

Travel distance and travel time

The first two indicators are Travel distance and travel time as short as possible; the lower the distance and/or travel time of a route, the less risk a cyclist is exposed to. To illustrate these indicators, *Figure 3.9* shows a map of the three OD-pairs and the distance and travel time of the routes.

OD-pair 1	Route 1B is shorter than route 1A in both distance and travel time.
OD-pair 2	Route 2A and 2B have the same travel time of 11 minutes, but route 2B is shorter in terms of distance.
OD-pair 3	The distance of 3.5 km is the same for both route 3A and route 3B, but route 3A is shorter in travel time.

Figure 3.9. Travel distance and travel time of the selected routes and their options



Intersection density

The third indicator is Low intersection density, especially concerning intersections with distributor roads. As (at-grade) intersections are risky places for cyclists, the lower the number of intersections, the safer the route. Moreover, intersections with distributor roads are known to be relatively unsafe for cyclists and for these intersections, roundabouts are preferred and signalised intersections are the least safe option. *Figure 3.10* shows the total number of intersections and types of intersections with distributor roads of the three selected routes.

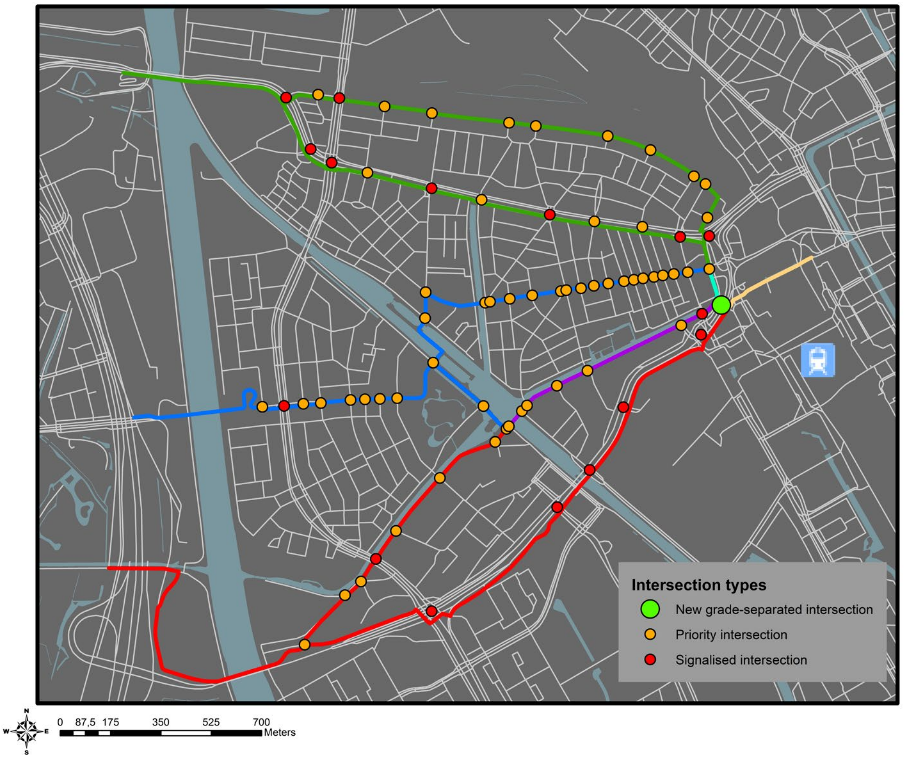
OD-pair 1 It can be seen that route 1A has more intersections on the route than route 1B. However, as the intersections of route 1A are mostly priority intersections with access roads and route 1B has more signalised intersections with distributor roads, it would be favourable for the safety of the cyclist to choose for option 1A.

OD-pair 2 Route 2A has more intersections than route 2B and both routes only have priority intersections. Therefore, it would be safer for a cyclist to choose for route 2B rather than for route 2A.

OD-pair 3 The number of intersections on route 3B is lower than on route 3A. However, the intersections on route 3A are mostly priority intersections, while at route 3B there are mostly signalised intersections.

To achieve safer intersections on the selected routes, intersections with distributor roads should be grade-separated wherever possible. *Figure 3.10* shows a possible location for a new tunnel for cyclists to pass a large intersection with multi-lane distributor roads. This would create a safe solution to cross these roads for several routes (1, 2, and 3A) and might attract cyclists who want to avoid signalised intersections with distributor roads on other routes (3B).

Figure 3.10. Intersection types on the selected routes and their options.



Exclusive bicycle tracks and separated bicycle tracks
The next two indicators are Wherever possible, cyclists should follow exclusive bicycle tracks, and Wherever possible, the use of 50 km/h distributor roads without separate bicycle tracks should be avoided. As it is preferred that cyclists are separated from motor vehicles as much as possible, it is desired that cyclists follow exclusive bicycle tracks as much as possible. However, it is unrealistic to achieve that all routes fully follow exclusive bicycle tracks. It is therefore desired that cyclists are separated from heavy and fast motorised vehicles at 50 km/h distributor roads by means of bicycle tracks or use access roads. For access roads with a flow function for cyclists, it may be desired to implement a bicycle street.

In *Figure 3.11*, it can be seen that the example network already has some exclusive bicycle tracks. However, the share of exclusive bicycle tracks is rather low in the existing network. It is therefore important to investigate where new exclusive bicycle tracks can be realised. This can either be a new path or an existing road transformed into an exclusive bicycle track. For the latter option it is important to find roads that are redundant in the network and for which other options for motor vehicles are available in the network. It is beyond the scope of this study to also include motor vehicle volumes, but if the aim is solely on bicycle flows some of the roads can be transformed into exclusive bicycle tracks. *Figure 3.11* shows the existing and possible new exclusive bicycle tracks in the example network and on the selected routes. The map also shows the bicycle streets in the network, which are located on the selected routes. These are mostly access roads that connect loose ends of the exclusive bicycle tracks and are transformed intro bicycle streets in order to adapt the infrastructure to bicycle through-traffic. The remaining access roads should be designed for safe mixing of different types of traffic. Lastly, the maps shows that all distributor roads already have separated bicycle tracks.

OD-pair 1 As can be seen on the map in *Figure 3.11*, route 1A could possibly be improved by implementing an exclusive bicycle track. Further research is needed to decide whether this is practically feasible. In case exclusive bicycle tracks could be realised, route 1A is preferred over route 1B as the latter mainly follows separated bicycle tracks along distributor roads. Although separated bicycle tracks are a safe solution for relatively unsafe roads, conflicts may arise at intersections with turning vehicles. Therefore, it is safer for cyclists to follow route 1A, as the number of conflicts with motor vehicles is minimised after implementing the exclusive bicycle track.

OD-pair 2 Route 2B could possibly be improved by implementing exclusive bicycle tracks (when practically feasible). This would make a large difference compared to route 2A, which has a large share of access roads. It is safer for cyclists to follow exclusive bicycle tracks than access roads. Therefore, in that case, route 2B is preferred over route 2A.

OD-pair 3 Route 3A could possibly be improved by implementing exclusive bicycle tracks on part of this route (when practically feasible). Compared to route 3B, route 3A is preferred, as route 3B fully consists of separated bicycle tracks along distributor roads.

After improving the network with the implementation of exclusive bicycle tracks, for every route one of the options became safer compared to the other options.

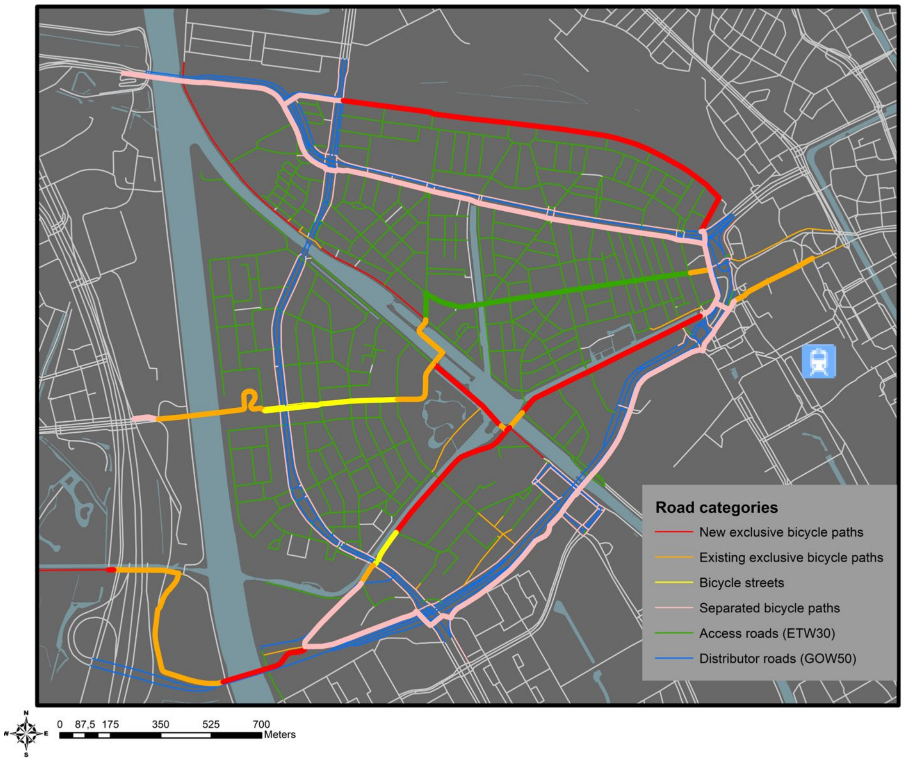


Figure 3.11. New and existing cycling infrastructure and road categories on the selected routes and in the example area.

Left-turns

The seventh indicator is <u>As few left-turns as possible</u>, as left-turns are risky manoeuvres for cyclists. *Figure 3.12* shows the left-turns in the selected routes when traveling from Leidsche Rijn to Utrecht Central Station.

OD-pair 1 Route 1A comes across two left-turns, while for route 1B this is only one. In terms of left-turns, route 1B would therefore be preferred over route 1A, although the difference is only minor.

OD-pair 2 Route 2A and route 2B both have one left-turn.

OD-pair 3 None of the routes for OD-pair 3 has left-turns.

It must be mentioned that the dark blue left-turn on route 2B is an intersection with solely exclusive bicycle tracks, which may differ in safety from a left-turn over an intersection with distributor roads. Furthermore, the light blue left-turn on routes 1 and 2A is a left-turn over a bidirectional bicycle track. The routes then cross a distributor, but this intersection is transformed into a tunnel at indicator 3. The most dangerous left-turn is therefore the green one at route 1A as this left-turn crosses an intersection of distributor roads. Note that this is a threelegged intersections and the left-turn therefore only crosses one road instead of two like at a typical left-turn on a four-legged intersection.

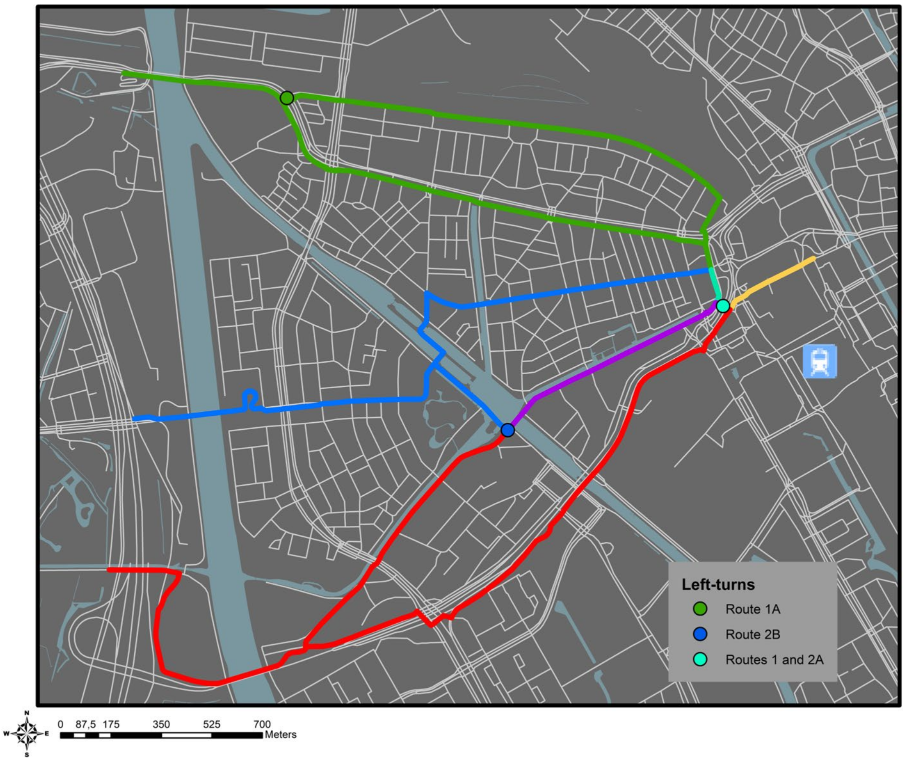


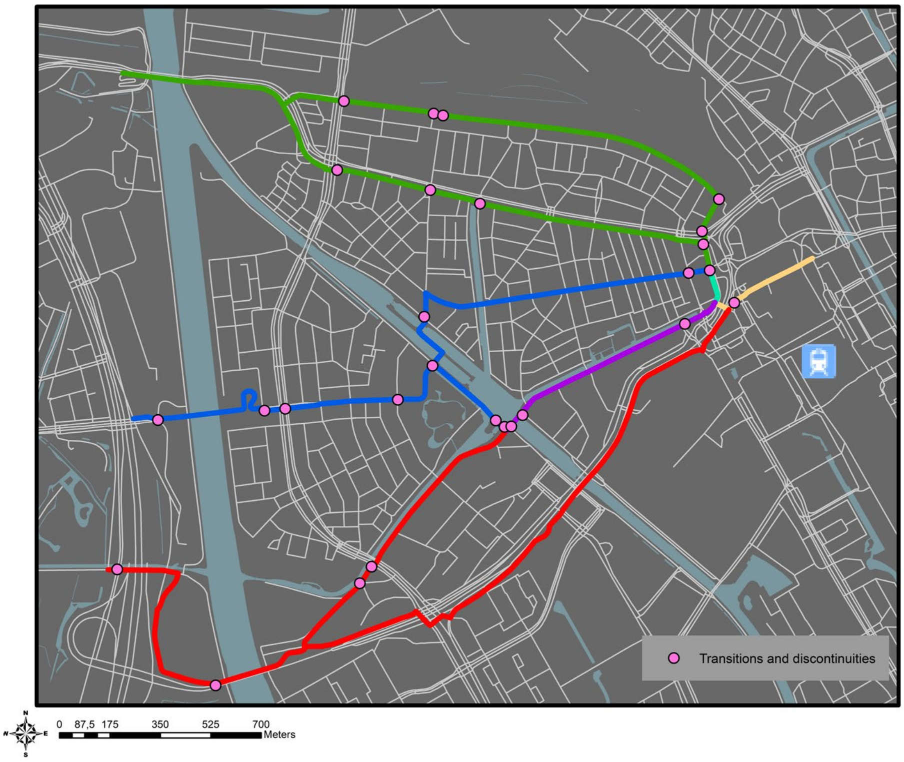
Figure 3.12. The left-turns on different route options.

Transitions

The eighth indicator is As few transitions and discontinuities as possible. These parts in the network may lead to increased risk of having a crash and can result in increased levels of discomfort. In *Figure 3.13* it can be seen that all routes have a certain number of transitions and discontinuities, mostly located at intersections. Although some transitions and discontinuities are unavoidable, they can be limited by continuing one road category as much as possible and avoiding switching between unidirectional and bidirectional bicycle tracks. The map shows the transitions an discontinuities as they are in the current network.

OD-pair 1	Route 1A has six transitions. Most of them are located at intersections to guide cyclists from one road category to another. Route 1B has five transitions of which most of them are a transition between unidirectional and bidirectional bicycle tracks. This shows it is sometimes unavoidable for cyclists to come across transitions as they are necessary to go from one type of cycling infrastructure to a another type of cycling infrastructure. However, the safety of Route 1B could be improved by consistently applying either unidirectional or bidirectional tracks.
OD-pair 2	Route 2A has nine transitions and discontinuities between different types of cycling infrastructure and road categories. Route 2B has eleven transitions and discontinuities. Option 2A would therefore be preferred over option 2B.
OD-pair 3	Route 3B has three transitions and discontinuities between different types of cycling infrastructure and road categories, which is lower than the eight transitions and discontinuities on route 3A. Route 3B would therefore be preferred based on the number of transitions and discontinuities.

Figure 3.13. The transitions and discontinuities on the different route options.



Bicycle through/flow traffic vs. vulnerable road users and 'residents'

The last indicator is Wherever possible, fast flowing and possible heavy (high weight) bicycle through-traffic should be separated from vulnerable bicycle traffic and 'residents'. This indicator aims to minimise serious conflicts between the most vulnerable road users (playing children, children on bicycles, seniors on bicycles) and potentially high speed and/or heavy (high weight) bicycles (and LEVs). It should be noted that there is no evidence for this indicator yet, so it is only for discussion. In case one would aim to realise the eighth indicator, it is desired to have a main corridor dedicated to bicycle through-traffic, on which they are separated from 'residents' and especially vulnerable bicycle exchange traffic. Figure 3.14 shows routes suitable for bicycle through-traffic and access roads suitable for bicycle exchange traffic. After applying the first seven indicators, the flow routes (here route 1A, 2B and 3A) mainly follow exclusive bicycle tracks.

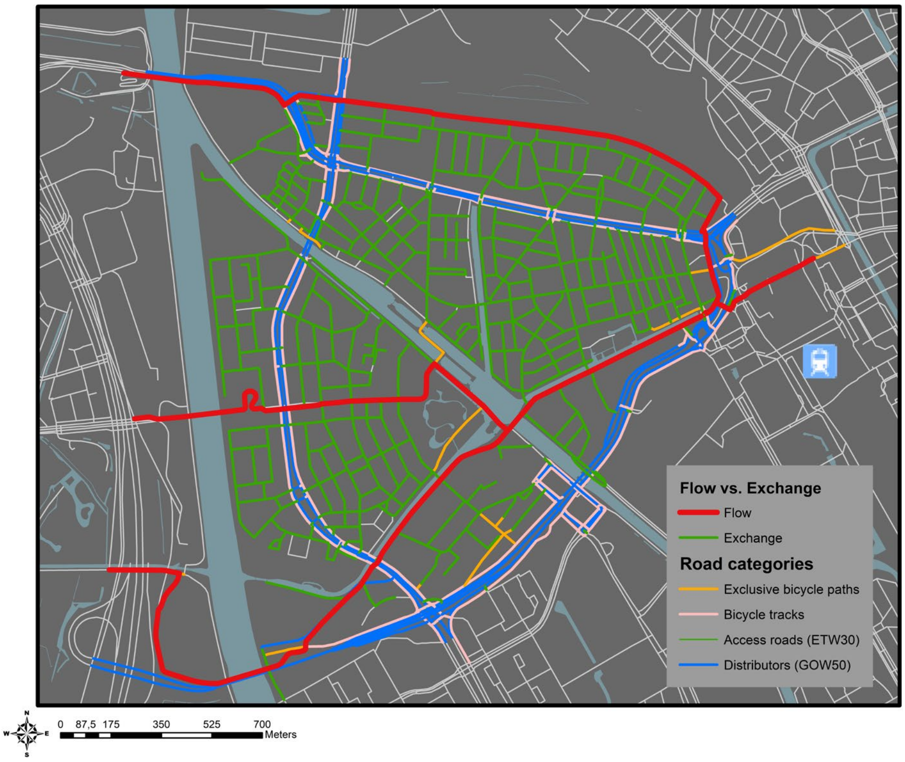


Figure 3.14. Bicycle flow and exchange infrastructure in the example area.

3.6 Summary

In order to improve the safety of cycling routes, road authorities can take measures at the network level, by changing the network structure or functional role of links in the network, or at the road level, focusing on the design of individual elements in the network. The eight indicators defined in *Section 2.4* can be used to identify places in the network where cyclists' route safety can be improved. We propose beginning with a network analysis in order to identify important cycling routes based on the existing travel demands and the network structure. These routes can subsequently be scored using the first seven route indicators. Where popular routes score badly, the choice can be made to make an existing route safer, create new safer alternatives, or make an already safer route more attractive to cyclists. Measures to create a safe route from new or existing infrastructure include:

- Maximise share of exclusive bicycle tracks in a route, especially for bicycle flow traffic
- Minimise share of routes along distributor roads without separate bicycle tracks
- Grade-separate bicycle intersections with distributor roads, for example with a bicycle tunnel or overpass
- Avoid left-turns and transitions between infrastructure types which require cyclists to cross motorised traffic
- Minimise route length
- Ensure road and bicycle infrastructure meet SPI guidelines for safe infrastructure design

In the example neighbourhood in Utrecht, three origin-destination pairs (OD-pair) were identified between Leidsche Rijn and Utrecht's central train station. For each OD-pair two route options were explored which each appear to serve large volumes of bicycle traffic. The safety of the example routes could be improved by implementing a bicycle tunnel at a busy distributor road intersection, creating new exclusive bicycle tracks, reducing transitions switching between uni- and bidirectional bicycle tracks, and increasing the attractiveness of the identified flow routes for flow bicycle traffic.

4 Conclusions and recommendations

Cycling is healthy, environmental friendly, space-efficient and cost-effective and therefore an attractive alternative to other modes of transport in urban areas. To ensure a safe increase in cycling, it is important to have a well-developed safe cycling network. Studies investigating safe cycling often focus on design choices at the road level, whereas also the route and network levels are relevant. Even when individual road sections in the network are safely designed, alternative routes or network structures may provide higher levels of safety.

This study dealt with cycling safety on the route level. First of all, it aimed to define indicators to compare the safety levels of different routes between one OD-pair. Second, it aimed to discuss how these indicators can be applied by road authorities in order to assess and improve the safety of cycling routes on their road network. Finally, it also aimed to discuss the function of different types of infrastructure in the cycling network. The focus of this study was on cyclist routes within urban areas (built-up areas). This chapter presents the main conclusions and recommendations.

4.1 Conclusions

4.1.1 Safe route indicators

On the basis of a literature review, Sustainable Safety and indicators for safe car routes proposed by Dijkstra (2011), we propose the following seven indicators for safe cycle routes:

1. Travel distance as short as possible: The lower the distance, the lower the exposure to risks
2. Travel time as short as possible: The lower the travel time, the lower the exposure to risks
3. Low intersection density, especially concerning intersections with distributor roads: The probability of conflicts is high at (at-grade) intersections and therefore a higher intersection density increases the probability of a crash. Intersections with distributor roads are the least safe for cyclists, and for these intersections, roundabouts are preferred and signalised intersections are the least preferred.
4. Wherever possible, cyclists should follow exclusive bicycle tracks: Exclusive bicycle tracks are (when designed in a safe manner) the safest option for cyclists as conflicts with motor vehicles are not possible.
5. Wherever possible, the use of 50km/h distributor roads without separate bicycle tracks should be avoided as much as possible: When speeds are higher than 30km/h, conflicts between motorised traffic and cyclists should be prevented. Therefore, roads with a 50 km/h speed limit or higher should have a separated bicycle track.
6. As few left-turns as possible: Left-turns at intersections are known to be a risky manoeuvre for cyclists. They should therefore be as limited as possible in a route.
7. As few transitions and discontinuities as possible: Transitions between and discontinuities of cycling infrastructure lead to increased risk of having a crash.

These seven indicators focus on limiting exposure and conflicts with motorised traffic. In addition, it might also be necessary to protect the most vulnerable road users (pedestrians and vulnerable cyclists) from large flows of fast-flowing and potentially higher weight bicycle through-traffic and other potential users of bicycle facilities, like the upcoming Light Electric Vehicles (LEVs). An additional indicator dealing with this issue is:

8. Wherever possible, fast flowing and possibly heavy (high-weight) bicycle throug-traffic should be separated from ‘residents’ and vulnerable bicycle traffic.

Unfortunately, research related to this indicator is very limited, which makes it difficult to present evidence for this indicator. However, the suggested indicator is in line with suggestions from other parties like Fietsberaad and the Dutch Cyclists’ Union.

4.1.2 Application of indicators

Between a given origin and destination (OD-pair) in the network, in general several route options are available. The safe cycling route indicators outlined in the previous section and discussed in more detail in *Section 2.4* can be used to compare the safety of these different routes and identify locations in the network where route safety can be improved. Building safe route options, however, only adds to cyclist safety if the safe routes are actually chosen by cyclists. It is therefore important to consider travel demands between different areas in the network as well as cyclists’ route preferences (e.g. travel time, environment, comfort) such that the safest routes are also most often chosen. We propose three primary steps in order to apply the safe route indicators at the network level:

1. **Network analysis:** Identifying routes of interest between important OD-pairs in network
2. **Route safety assessment:** Evaluating routes of interest using safety indicators
3. **Upgrade network:** Selecting measures to improve route safety

In order to improve the safety of cycling routes, road authorities can take measures at the network level, by changing the network structure or functional role of links in the network, or at the road level, focusing on the design of individual elements in the network. Where popular routes score badly, the choice can be made to make an existing route safer, create new safer alternatives, or make an already safer route more attractive to cyclists.

In the example neighbourhood in Utrecht, three origin-destination pairs (OD-pair) were identified between Leidsche Rijn and Utrecht’s central train station. For each OD-pair two route options were explored which each appear to serve large volumes of bicycle traffic. The safety of the example routes could be improved by implementing a bicycle tunnel at a busy distributor road intersection, creating new exclusive bicycle tracks, reducing transitions switching between uni- and bidirectional bicycle tracks, and increasing the attractiveness of the identified flow routes for flow bicycle traffic.

4.1.3 Function of different cycling facilities

As shown in *Table 4.1*, exclusive bicycle tracks are preferred to serve large volumes of probably relatively high speed through cyclists. Access roads, depending on their characteristics, can either be adapted to serve (larger volumes of relatively high speed) through bicycle traffic or mainly serve local traffic. Bicycle streets, while requiring further research into their safety and ideal characteristics, may be an option to serve fast-flow cyclists on access roads when exclusive bicycle tracks are not feasible. Distributor roads are primarily intended for motorised through-traffic and can potentially serve a function for bicycle through-traffic as well. However, due to the high motorised traffic speeds it is important that physically-separated bicycle tracks are present and intersections are minimised and designed as safely as possible.

Table 4.1. Proposed functions of different cycling facilities in the network

Infrastructure category	Important characteristics	Primary function for motor vehicles	Primary function for cyclists
Exclusive bicycle tracks	› Wide enough to support variety of bicycle types and speeds › High bicycle traffic volume › Low adjacent pedestrian volumes › Few intersections, side-roads › Safe track-side verges › Bidirectional bicycle traffic	n/a	Flow
Access roads: flow	› Potential bicycle streets › Low motorised traffic speeds › Low motorised traffic volumes › Minimal exchange traffic › Few intersections, side roads	Exchange	Flow
Access roads: exchange	› Traffic calming › Lower cycling speeds to protect vulnerable cyclists and pedestrians › Low motorised traffic speeds › Low motorised traffic volumes	Exchange	Exchange
Distributor roads	› Separate bicycle track › Uni- or bidirectional bicycle traffic › Avoid at-grade intersections	Flow	Flow

4.2 Recommendations

4.2.1 Recommendations for policymakers

Policymakers and road authorities can identify measures to improve the safety of cycling routes at both the network level and the road level. In order to identify routes of interest at the network level, we recommend beginning with a network analysis. Following this, routes can be assessed using the safe route indicators proposed in *Chapter 2* to assess and compare the routes as a whole, as well as the Safety Performance Indicators for safe road design and safe cycling infrastructure provided by the Kennisnetwerk SPV to assess the safety of individual road sections. Based on this assessment, places in the network can be identified to improve infrastructure safety. Measures to create safer cycling routes following from the safe route indicators (at the network level) and the Safety Performance Indicators (at the road level) are summarised in *Table 4.2*.

In existing networks, the measures can be used to make improvements at locations with high safety risks, for example by adding a tunnel for cyclists to avoid crossing a busy distributor road. The indicators can also be used to help guide the design of new routes and new networks. Due to a high demand for housing, it is likely that new residential developments will be built in the coming years. Rather than considering traffic safety only at the last step, with just road-level design measures after the structure has been decided, cycling safety can be further improved by considering safety of the cycling network in the first stages of planning the network structure. By designing the network such that cyclists are exposed as little as possible to (especially fast-moving) motor vehicle traffic, cyclists will experience less safety risks. This means designing a cycling network such that the fastest and most attractive routes follow (sufficiently wide and forgiving) exclusive bicycle tracks, access roads or separated bicycle tracks; minimising intersections and left-turns especially involving distributor roads; and creating a consistent protected network with limited disruptions.

Table 4.2. Network- and road-level measures for safe cycling routes

Approach	Measures for safe cycling routes
Network-level measures	- Separate motor vehicle flow traffic from access roads and bicycle traffic - Create direct cycling routes with minimal detour - Create exclusive bicycle tracks where possible - Create bicycle through-routes on exclusive bicycle tracks - Low motorised and bicycle traffic speeds on roads with strong exchange function - Introduce grade separation or avoid cycle route intersections with distributor roads - Avoid left turns and transitions between infrastructure types which require cyclists to cross with motorised traffic - Make safe routes more attractive to cyclists, for example by increasing comfort or adapting traffic light settings
Road-level measures	- Create separated bicycle tracks along distributor roads - Limit speeds where conflicts between cyclists and motor vehicles can occur - No obstacles in the cycling infrastructure - Sufficiently wide bicycle tracks - Quality surface: smooth, complete, clean, not slippery - Visual guidance - Forgiving track edges and verges

4.2.2 Limitations and recommendations for further research

A couple areas are identified for further research. Firstly, while the first seven indicators have each been shown across various studies to have a relationship with bicycle safety, the operationalisation and combination of this particular set of indicators into a total route safety score has not been validated with crash data. Further research would be necessary in order to quantify a relationship between total route safety scores and crash rates along a route. This would also be necessary in order to determine weights for the contributions of each indicator to a total route safety score. Without such a quantitative validation, the indicators as proposed in this study are primarily intended for a qualitative comparison of routes in order to identify safety concerns in the network and clarify preferences for safe cycling routes.

A type of infrastructure which has been increasing in number in recent years and warrants extra attention is the bicycle street. A bicycle street is a street in which cyclists are considered to be the most important road users; cars are allowed, yet, considered to be ‘a guest’ in these streets. Where realising an exclusive bicycle track is not feasible, bicycle streets can potentially offer cyclists a more comfortable alternative to traditional access roads. Bicycle streets, when implemented on access roads with lower levels of exchange/residential traffic, may also be a form of infrastructure which can attract through-cyclists away from exchange areas. However, there is large variation across current bicycle street designs and more research is necessary to determine their impact on cyclist safety.

Lastly, the first seven indicators are aimed at reducing the frequency and severity of conflict possibilities between cyclists and motor vehicles, as these conflicts are more likely to lead to serious injury or death. However, single bicycle crashes and conflicts with other cyclists or pedestrians can also occur. Regarding single bicycle crashes, available research mostly points to the importance of safe road-level design such as the removal of obstacles, clearly marked and forgiving edges/verges and wide enough tracks—factors which are considered in the road-level Safety Performance Indicators. However, research is lacking on the risk of a single bicycle crash, bicycle/bicycle crash or bicycle/pedestrian crash on different types of facilities. The eighth proposed indicator—separating faster-moving and possibly heavier-weight bicycle flow traffic as much as possible from areas with a residential function/higher level of exchange traffic—is a possible approach to limiting the frequency and severity of bicycle/bicycle and bicycle/pedestrian conflicts at the route level. Nevertheless, further research is necessary to validate this indicator’s relationship to safety, for example by studying the causes and nature of cyclist accidents not involving a motor vehicle. Regarding the feasibility of this indicator, future research may also investigate the relation between variation in cycling speeds and types of cycling facilities.

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Appendix A Translations

English translation	Dutch
Access road	*Erftoegangsweg*
At-grade intersection	*Gelijkvloers kruispunt*
Verge	*Berm*
Bicycle lane	*Fietsstrook*
Bicycle track	*Fietspad*
Bicycle street	*Fietsstraat*
Distributor road	*Gebiedsontsluitingsweg*
Exchange function	*Uitwisselingsfunctie*
Exclusive bicycle track	*Solitaire fietspad*
Flow function	*Stroomfunctie*
Grade-separated intersection	*Ongelijkvloers kruispunt*
Intersection	*Kruispunt*
Road section	*Wegsegment*
Road transition	*Wegovergang*
Through road	*Stroomweg*

Appendix B Safe cycling indicator calculations

This appendix outlines how the safe cycling indicators are calculated to achieve the route stars presented in *Section 3.5.2.* For most of the indicators ArcMap is used to retrieve the information from the network and Microsoft Excel is used to calculate the scores for the indicators. The cycling network file is provided by the Dutch Cyclists' Union and contains information about the cycling infrastructure as well as intersection types. Google Maps was used to calculate the travel time for indicator 2 and Google Street View for indicator 8 to inspect the routes for transitions and discontinuities.

1. Travel distance as short as possible:

This is the sum of the length in kilometres of all road sections in a route. In our study, ArcMap is used to summarise the link length. A shorter distance leads to a higher score.

2. Travel time as short as possible:

The travel time of a route is calculated on Google Maps and is based on the travel time for cyclists. It is unknown how this travel time is calculated by Google. A lower travel time leads to a higher score. When data is available about average cycling speeds per road section and waiting time at intersections, the travel time can be calculated without using Google Maps.

3. Low intersection density, especially with distributor roads:

Intersection density = number of intersections / length of the route. A lower intersection density leads to a higher score.

Please note that all intersections are taken into account in this item. One could also further specify this indicator, distinguishing between access roads and distributor roads.

3a. Roundabouts:
The sum of the number of roundabouts in a route. A higher number of roundabouts leads to a higher score.

3b. Priority intersections:
Not calculated, as this is the middle category in the ranking order of safety of intersection types.

3c. Signalised intersections:
The sum of the number of signalised intersections in a route. A lower number of signalised intersections leads to a higher score.

4. Cyclists should follow exclusive bicycle tracks as much as possible:

Proportion exclusive bicycle track = length of exclusive bicycle track / length of route. A higher proportion of exclusive bicycle tracks leads to a higher score.

5. The use of 50km/h distributor roads without separated bicycle tracks should be avoided as much as possible:

Proportion separated bicycle tracks: length of separated bicycle tracks / length of distributor roads. A higher proportion of separated bicycle tracks leads to a higher score.

6. As few left-turns as possible:

Sum of the number of left-turns. A lower number of left-turns leads to a higher score.

7. As few transitions and discontinuities as possible:

Sum of the number of transitions and discontinuities. A lower number of transitions and discontinuities leads to a higher score.

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