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Safety assessment and design considerations of unidirectional cycling infrastructure in the city of Espoo

Thesis submitted for examination for the degree of Master of Science in Technology

Espoo 25.05.2020
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Title of thesis: Safety assessment and design considerations of unidirectional cycling infrastructure in the city of Espoo
Master programme: Spatial Planning and Transportation Code: ENG26
Thesis supervisor: Miloš Mladenović
Thesis advisor: Hamilkar Alava Bergroth
Date: 25.05.2020
Number of pages: 91+9
Language: English

Abstract
While increasing cycling mode share, it is paramount not to compromise the safety of cyclists. The design of cycling infrastructure has been shown to be an important factor for safety. One aspect of design is the directional flow of cyclists assigned by the cycle paths. In Finland, bidirectional shared paths with pedestrians have traditionally been the way of designing cycling and walking infrastructure. Previous research on bidirectional cycle paths has indicated safety issues, especially at intersections. Drivers reportedly pay less attention to cyclists approaching from the unexpected left side of the street, with a travel direction that differs from that of the adjacent motor vehicles. In contrast, when unidirectional design is chosen, there could be several advantages from the safety perspective. This thesis evaluated the safety of bidirectional cycle paths in the city of Espoo, in an attempt to discover the safety-related issues and possibilities for the current design. Triangulation was used as a combination of methods to study the issue from complementary angles. An accident data analysis was done to locate the extent and qualities of the safety issues with bidirectional paths from the previous ten years in the city of Espoo. Conflict analyses for two sites were carried out to spot safety related aspects at unsignalized intersections, and to understand potentials for intersection redesign. Finally, an expert workshop provided input in terms of design considerations.

More than a quarter of all cycling accidents, and 60 percent of those with crossing travel directions had cyclist travelling on the left side of the street. These could arguably be addressed with unidirectional design. Largely, these accidents were located on major street classes with give-way (yield sign) intersections. In accidents with crossing travel directions, the cyclist was most commonly approaching the intersection along the priority street, with the driver on the secondary street. Turning accidents with both road users on the priority street were equally common. The conflict analyses revealed a problem with an insufficiently wide waiting area when turning away from the major street. The results from the workshop were supportive of unidirectional design in Espoo and included considerations in line with the state-of-the-art design literature. The considerations for intersection treatments are mainly aiming at traffic calming and ensuring visibility between road users. These design aspects are achieved for instance with segregating cycling facilities, deflecting the cycle path and creating a designated waiting area for the motor vehicles, or by aligning cyclists closer to increase visibility. The chosen solution is always a compromise between different criteria for design and available resources. Future activities for developing design practice should pay attention to historical safety data, rely on conflict point analysis, improve data collection procedures, and elaborate design as an iterative process.

Keywords: cycling, unidirectional, one-way, bidirectional, infrastructure, design, safety, accident, conflict
Tekijä: Pieta Haukka

Työn nimi: Yksisuuntaisen pyöräilyinfrastruktuurin turvallisuus Espoossa

Maisteriohjelma: Maankäytön suunnittelu ja liikennetekniikat
Koodi: ENG26

Työn valvoja: Miloš Mlandenović

Työn ohjaaja: Hamilkar Alava Bergroth

Päivämäärä: 25.05.2020, Sivumäärä: 91+9, Kieli: englanti

Tiivistelmä


Avainsanat: pyöräily, yksisuuntainen, kaksisuuntainen, infrastruktuuri, suunnittelu, turvallisuus, onnettomuus, konflikti
Preface

The objective of this thesis was determined in collaboration with the city of Espoo that is currently working on updating their guidelines for street design. The directional flow enabled with cycling infrastructure is something the new guidelines will address. This thesis is part of a larger project which aims at determining whether and how the city of Espoo will incorporate unidirectional cycle paths on their cycling design paradigm. The larger project includes spatial and budgetary considerations.

I appreciate the opportunity the city of Espoo has offered me. Special thanks go to Kristiina Kartimo for helping clarify the aim of the thesis and advising along the process. I would like to thank everyone else involved: my supervisor Miloš Mladenović (Aalto University) for his extensive counsel, my advisor Hamilkar Alava Bergroth (A-Insinöörit Civil Oy) for all the help and support, and Aapo Lumikoivu (Aalto University) for enabling the technical parts. Finally, I would like to thank my family and friends for their support.

Espoo 25.5.2020

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| Concepts | | | |
|---|---|---|
| **Bidirectional cycle path / BCP** | Kaksisuuntainen pyörätie | Cycling facility with flow for both directions, can be separated with markings, can include pedestrians. |
| **Bilateral cycle paths** | Molemminpuolinen pyöräteijärjestely | A design solution with cycle paths on both sides of the street. |
| **Contraflow cycle lane** | Vastavirtakaista (polkupyörille) | Bilateral cycle lanes on a one-way street (for motor vehicles). "Illegal contraflow" is used when referring to cycling against the flow of unidirectional path. |
| **Cycle lane / bike lane** | Pyöräkaista | Longitudinal section of carriageway for cyclists along (urban) street. Separated with road markings or paintings from motor vehicle traffic. |
| **Cycle path / bike path** | Pyörätie | Any cycling specific facility. Includes separated cycle tracks and cycle lanes as well as solitary cycle paths. Can flow unidirectionally or bidirectionally. |
| **Cycle track** | Korotettu pyörätie | Cycle path that is separated physically from motor vehicle traffic. |
| **Shared use ("light traffic") path** | Kevyen liikenteen väylä | Bidirectional cycling and walking path separated physically from motor vehicle traffic. |
| **Solitary cycle path** | Erillinen pyörätie | Cycle path without an adjacent street in close proximity. Usually shared with cyclists and pedestrians. |
| **Three-level solution** | Kolmitasoratkaisu | Cycling separated physically (vertically) from both motor vehicles and pedestrians. |
| **Unidirectional (One-way) cycle path** | Yksisuuntainen pyörätie | Cycle path where only one-way flow is allowed. Usually adjacent to main street flow. |
| **Unilateral cycle path** | Yksipuolinen pyöräteijärjestely | A design solution with cycle path on only one side of the street. |
1 Introduction

Increased cycling has multiple potential advantages for both the individual and for the society. The transportation planning system is being continually renewed in Finland, which enables for more people to make the modal shift. While increasing cyclist modal share, it is paramount not to compromise the safety of cyclists. One aspect of design is the directional flow of cyclists. Bidirectional shared cyclist and pedestrian paths have long been the way of designing cycling and walking also in urban environments, until more recent advances. The bidirectional paths have been associated with safety problems, whereas unidirectional facilities can increase safety, if they are implemented well (Thomas and DeRobertis 2013). Unidirectional cycling is not a new invention. Before cycling facilities were introduced, cyclists travelled on the carriageway among motor vehicle flow, when the volumes were lower. European countries, such as Denmark and The Netherlands have had unidirectional cyclist specific facilities for decades, and with great results. These countries have both high numbers of cyclists and low numbers of cycling accidents. Although the relationship between increased cycling and safety has been observed (Jacobsen 2015), the design of cycling facilities has also been shown to be an important factor for cyclist safety (Reynolds et al. 2009).

The goal of this thesis is to provide support for the city of Espoo in determining the future cycling design paradigm: whether and how to start designing unidirectional cycling on urban areas. More accurately, this thesis explores the extent and qualities of a safety potential for unidirectional cycling facilities. For those situations, literature findings of design solutions concerning the safety perspective are evaluated. This thesis is a part of a larger project concerning the new shift of paradigm. The project as a whole includes a detailed spatial study on where unidirectional design could be applied, along with cost evaluations.

The background part consists of a review of the literature concerning safety and design considerations related to unidirectional cycling. Unidirectional facilities are reviewed on a general level, on their effect for intersections, road sections and for the transport network. The empirical part of this thesis consists of an accident data analysis from the previous 10 years, conflict analyses of two sites and a workshop concerning the professional and user input of unidirectional cycle path considerations for Espoo.

The research angle of this thesis is safety, while other criteria are covered briefly when they are relevant. Similarly, other aspects such as fluency and budgetary considerations are addressed in relation to safety, while some, such as demographics or policy are left out. The distinct safety features that are studied are those related to design of a street design scale, while the very detailed design (inclination, grade, equipment etc.) or network level are not addressed extensively. Because of the nature of unidirectional cycling, safety is considered primarily in its relation to motor vehicle traffic on urban areas. This means leaving out solitary cycle paths and rural roads, but addressing to some extent situations between cyclists themselves, and with pedestrians.

The different approaches were brought together in an attempt to answer the following research questions:

- How does unidirectional cycling design affect cyclist safety?
- What is the extent and quality of the traffic safety conditions in Espoo that unidirectional design could potentially cater for?
- What design factors could improve the safety of unidirectional cycling facilities?
2 Background

The popularization of passenger cars in Finland starting from the 1960s resulted with cycling being separated from the faster motor vehicle traffic. The design of cycling and walking in Espoo and the rest of Finland has been following the SCAF design philosophy that came out from Sweden in the late 1960s. According to SCAF, cyclists and pedestrians are clumped together and separated from motor vehicles. In 1998 The Transport Agency of Finland published a manual for designing “light traffic”. The guidelines for street design in Espoo were published in 1998 and revised in 2010 (City of Espoo 2010).

In the 2010s SCAF has been criticized for not differentiating between the needs of cycling and walking as modes. In 2011 the Ministry of Transport and Communications developed a national strategy to increase cycling and walking and started to consider them as separate modes. Consequentially, they stopped using the concept of “light traffic”. In 2014 Transport Agency of Finland published a guide for designing cycling and walking, that is applicable on urban areas (FTIA 2014a). The planning and design knowledge of cycling has increased recently along the new design principles of the city of Helsinki (2016), which are heavily influenced by other European design practices. The following chapter presents the characteristics of transportation in Espoo to provide a context.

2.1 Cycling in Espoo

Espoo is located on Uusimaa, within the Capital Region. It is the second largest city in Finland with 281,742 inhabitants and 312 km² land area (City of Espoo 2018). The city structure of Espoo consists of five city centers: Espoon keskus, Leppävaara, Tapiola, Matinkylä and Espoonlahti which are connected with metro, train, motorways and ring roads. There is great variance within Espoo, as the city centers are denser, and the areas in between are suburban or rural. North of Espoo is less densely built with worse accessibility than the southern part of the city. In 2017, the annual vehicle kilometers travelled (VKT) figure was 1650 million (City of Espoo 2019a), of which more than 60% occurs on the motorways and ring roads, and 28% on the street network (City of Espoo 2019c). The volumes are depicted on City of Espoo (2019b, p. 34).

Currently, there are approximately 893 km of pedestrian and cycle paths in Espoo (City of Espoo 2019a). The modal share of cycling trips made has varied between the years and is currently approximately the same as in the rest of Helsinki Region: 8% (on autumn weekdays, City of Espoo 2019b). Based on cyclist calculations on summer seasons, the numbers have fluctuated annually but remained overall quite the same in the past ten years, though in 2019 the average cyclist volumes increased 16%. The shared city bikes became available in Espoo in 2018, and they have gathered users, especially in relation to transit stations as feeder transport. (City of Espoo 2019b). Shorter trips are done usually in urban areas where other traffic modes mix. These are also the places where unidirectional cycling is applicable.

The EU PRESTO project produced a model of dividing cities into three groups based on their cyclist modal share and cycling conditions: starters, climbers and champions. There are different means cities in different stages should do to improve cycling. The “champion cities” have fewer cycle paths than starters or climbers, but they are of greater quality and uniform throughout the street sections. (Vaismaa 2014). Espoo is ranked somewhere
among the “starter” groups with a less than 10% cyclist modal share, history of car-oriented planning effecting on land use, streets, intersections and parking. For starter cities it is important to implement high quality major connections from residential areas to centers (Vaismaa 2014).

Advances in cycling have been done in Espoo. In 2013 Espoo announced their cycling promotion plan (City of Espoo 2013). The municipality is currently developing cycling superhighway connections between the centers. The cycling promotion plan set two strategic goals for cycling: Espoo will be a model city for travel chains and quality paths, and cycling modal share will rise to 15% of trips made by the year 2024 (City of Espoo 2013). Espoo will develop guidelines that set the future paradigm for designing cycling. The question of cyclist directional flows will be addressed in the new design, and this thesis seeks to provide background information for it. Key issue is how to increase cycling modal share without compromising safety.

Currently, traffic in Espoo is very safe compared to other Finnish cities and it has continually become safer (apart from the local peak of 2011). The details of cycling accidents are covered extensively in this thesis, as the primary methodology is the accident data analysis. Key figures concerning traffic safety in Espoo during 2009-2018, reported by the police (Destia 2019):

- 5430 traffic accidents
- 33 deaths and 1386 injuries.
- Proportionally 41 bodly injury accidents per 100 000 inhabitants (which is less than half of the national average).
- 47% of the traffic accidents occurred on street areas.
- 196 cycling related accidents, which accounts for nearly 4% of all accidents.
- 167 (85%) of the cycling accidents lead to an injury and 6 (3%) were fatal.
- 15% of all accidents leading to bodily injuries included cyclists.

Most of the cycling accidents occur at urban areas. Total estimated annual costs of traffic accidents are 31.6 million euros of which 6.3 million falls for the municipality (City of Espoo 2019c). The public transit system in Espoo is well connected to the dense city structure around the city centers with good accessibility. An important reason explaining the safety of cycling in Espoo is the separation of intersecting modes that is achieved with elevated intersections, underpasses and overpasses for cyclists. The areas around schools are well designed, and the city structure in the proximities are dense, which shortens the trips done by children and has resulted in a small number of accidents. (City of Espoo 2019c). Special attention on signal-control has increased safety. In 2019 there were 233 signal-controlled locations, including crossings on road sections as well as intersections. (City of Espoo 2019a). Though, there are bound to be some additional reasons that account for the differences. Around half of Espoo residents commute to another city (City of Espoo 2019c, p. 20), mainly to Helsinki, as there is a considerable job abundance compared to other cities. Some of the accidents occurring in Helsinki are coming from residents of Espoo, while accidents are usually compared to the population of the municipality.

On the street network most of the traffic is on the commercial concentrations. Streets in Espoo are divided into classes based on their functionality in the transport network. The practice of sometimes connecting local streets to main streets has been considered as unproductive for traffic safety (City of Espoo 2019c). Similarly to the functional classification of streets, since 2010 when the planning of cycling superhighways started, cycle
paths have been divided by their (planned) functionality on the cycling network (Figure 1). The planned superhighways are depicted with red.

The streets in Espoo have been constructed with relatively much space, as opposed to Helsinki, which is denser. The present cross section design guidelines from 2010 recommend separation for cyclists based on the street class. The current separation criteria between modes (Table 1) has largely been based on the SCAFT design philosophy. Shared pedestrian cycle paths are usually designed as 3 to 4 meters wide on main and local routes. With high cyclist and pedestrian volumes, they can exceed 4 meters (City of Espoo 2010). New considerations for cross-section design in varying environments were studied by Rautio (2019).
Cycling on the left side of the street can be (to an extent) removed with unidirectional cycle paths, which is the main point of this thesis, starting from chapter 2.4. Previously in Espoo, Manner (2015) found left-sided cyclist travel to be included with around 15% of the cycling accidents (2004-2013). So far virtually none of the road segments or junctions in Espoo are designed unidirectional with cyclist specific facilities. However, according to a Digiroad data study done by Ramboll (2020), there are multiple local streets where the cycling is mainly assigned to carriageways and not on specific facilities (the proportions ranging from 22 to 60% of districts).

The renewing planning guidelines will address the question of cyclist directional flow. As cycling in Espoo is increased and the street network is getting denser at urban places, unidirectional design can offer solutions to combat the safety issues of bidirectional paths. This thesis goes on to explore the effect of those solutions and the extent and qualities of the safety issues currently in Espoo.

### 2.2 Cycling legislation

In Finland, land use and transport planning are enacted by the Land Use and Planning Act. The land use of a municipality is organized and directed according to master plans and detailed plans, which are preceded by regional land use plans and national objectives (MRL 1999/132, 4 §). Most of Espoo has effective master plans or component master plans. In the parts where legally effective master plan does not exist, planning is guided by the regional land use plan (City of Espoo 2020). Like land use, transport is planned hierarchically from transport policy and regional planning (“transport master plans”) to a more detailed level (City of Espoo 2019e).

The construction of urban cycling infrastructure follows the regulations of the detailed plan of the area that is preceded by the master plan (MRL 1999/132, 35 §). The detailed
The Road Traffic Act (TLL 2018/729) is becoming active in June 2020, and it will replace the old legislation (TLL 1981/267). It includes some changes concerning cycling traffic. It is important to distinguish past legislation from the new (which has not been active during the writing of this thesis), especially when dealing with accident data which occurred when the old legislation was active.

**Place of the cyclist**

A bicycle is a non-motorized vehicle. The place of the cyclist (above the age of 11) is on the cycle track or, in the absence of it, on the right side of the carriageway (TLL 2018/729, 18 §). People travelling with rollerblades, skies, kick scooters and such are defined as pedestrians (TLL 2018/729, 2 §). When special reasons compel, a road user is allowed to momentarily shift from their place (TLL 1981/267, 8 §; TLL 2018/729, 18 §). For instance, a cyclist can remain on the carriageway when there is a short period with cycle path only on the left side of the street, and assuming the cycle path would increase danger. In the new legislation cycling is permitted on the right-side shoulder even if a left-side bidirectional cycle path exists (TLL 2018/729, 18 §). There has been a debate on whether cyclists are allowed to cross pedestrian crossings on saddle (without walking the bicycle). The legislation is not entirely unambiguous on it but according to Liikenneturva (2013) pedestrian crossings are considered as cycle path extensions even without the appropriate markings, if the cycle path continues after the carriageway ends. This was also demonstrated in a law case back in 1996 where the Supreme Court of Finland ruled in favor of cycling on a pedestrian crossing (KKO 1996:125). In the new legislation, it is clear that cyclists may cross the pedestrian crossing on saddle if they do not cause danger or trouble to pedestrians (TLL 2018/729, 18 §). In addition, pedestrians exiting trams or buses need to be given safe access while bypassing the vehicle from the right side (TLL 2018/729, 24 §). While the permission to cross is a precondition for right of way, but it does not designate it.

**Right of way**

As bicycles are (non-motorized) vehicles, while travelling on the carriageway, the general legislation of right of way applies to cyclists. By default, the road user must yield to the vehicles approaching from the right (TLL 2018/729, 24 §), which is called the right-hand rule. Right of way is assigned with signage that indicates right of way or yield, and they are placed on the right side of the street or cycle path (TLL 2018/729, 77 §). On top of that, signal control takes precedence over the signage (TLL 2018/729, 8 §). The right of way of cyclists travelling on solitary cycle paths crossing the street was changed in the June 1997 (TLL 1981/267 14 §). The 1997 law decrees that a cycle track extension intersecting motor vehicle traffic has no right of way, even when coming from the right, thus the cyclist yields, unless the right of way is changed by signage or signal control. In other words, the cycle path crossing the street is not considered as an intersection (where the
right-hand rule would apply). Karvinen (2012) found in a poll study that only 34% of the respondents knew the right answer to this particular question of right of way. Heterogeneity of the cyclist answers was notable, and there was a clear relationship with knowing the right of ways and owning a driving license. Fortunately, the road users that assumed the exceeded cyclist right of way were mostly drivers, and not the other way around. The same question was posed to 12-15-year-olds, of which 26% answered correctly (Nyman 2019).

**Signage**

Cycle paths are marked with the following signs (Figure 2): D5 (cycle path), D6 (shared cycle and pedestrian path), D7.1/2 (adjacent cycle and pedestrian paths), E13.1/2 (cycle lane) and E28 (bicycle street). Cycling marking on the pavement (M8) is used on cycle lanes, cycle tracks, cycle track extensions and cyclists’ waiting areas. (TLL 2018/729).

![Figure 2 Bicycle path signs: bicycle path (D5), shared path (D6), marking divided (shared) path (D7.1), bike lane (E13.1) (TLL 2018/729).](image)

Contraflow cycling means making a one-way street section bilateral (but unidirectional) for cyclists. By adding the sign C2 (motor vehicle driving prohibited) this has already been an option in the 1981 legislation, though it has been used rarely. The new legislation allows an arguably clearer way to assign bilateral cycling by accompanying the one-way travel sign (E14.2) or C17 (prohibited driving direction) with the sign H12.10 (bicycle, “does not apply”), shown on Figure 3. Contraflow cycling design for one-way streets is discussed further in chapter 2.5.1.

The 2020 legislation is set to remove right of way confusion among road users. The new sign B7 (yield cyclist at crossing, Figure 3) is to be used preferably on main cycle routes and only on physically ascended cycle path extensions (TLL 2018/729). The cycle path extension (B7) is by appearance and function the cyclist equivalent of the pedestrian crossing. In most cases the sign B7 can be replaced with a yield or a stop sign, though in some cases the solitary cycle path located too close to a minor street is given the right of way, when a yield sign would create confusion by being too closely associated with the minor crossing street (that yields to the major street). According to the new legislation it is mandatory to mark bidirectional cycle paths with a sign (H23.1, H23.2, H9.1 or H9.2, Figure 3) (TLL 2018/729). Cycle path extensions are to be marked accordingly in two years of the inception of the law, that is on 2022 June.
2.3 Safety factors

This chapter describes the scale and aspect this thesis is focusing on, and briefly covers other factors that are relevant for safety. Both the CROW manual and the manual of Helsinki lay out five key aspects of a cycling-friendly infrastructure: cohesion, directness, attractiveness, safety and comfort (CROW 2016, p. 31; City of Helsinki 2016, p. 27). FTIA (2014a, p. 27) lists design goals perceived by the cyclist: fluency, comfortability, safety and swiftness. Ensuring adequate flow and safety of cycling routes is stressed in the Espoo cycling advancement plan (City of Espoo 2013). The chosen solution is always a compromise between different aspects, of which safety is paramount. The aspects are connected to one another. Safety is not only a measure of accident count but also severity. However, the literature and accident data reviewed in this thesis often have little distinction on severity by differentiating only between death, injury and material damage (apart from Kaplan et al. 2014 and Kim et al. 2007).

Achieved safety is a sum of different factors such as transport policy, legislation, design, education and culture. This thesis covers the factors concerning infrastructure design, and to some extent the network level of planning. The focused aspect is actual traffic safety, excluding perceived safety. However, perceived safety should not be ignored in design as it can increase cycling volumes (Thomas and DeRobertis 2013) and serve as a proxy for overall cycling safety. Increasing perceived safety can be in line with actual safety, with for instance segregated facilities (Chataway et al. 2014).

Ideally, the intertwinement of the design aspects creates a feedback loop. Attractiveness, cohesion, directness and comfort of cycle paths are bound to increase cyclist modal share. Increased cycling in turn is associated with increased safety (Jacobsen 2015; Luukkonen and Vaismaa 2013), and the higher the modal share, the more feasible it is to allocate further resources to improve cycling. There are multiple ways of affecting traffic safety with planning and design. The factors are here divided by the scale from macro to meso and micro (Figure 4), and this thesis focuses on meso scale infrastructure. Aside from design, cycling safety affected by policy and legislation that account for instance for available resources, speed limits and right of ways.
Figure 4 Factors affecting cycling safety design can be divided to three scales. The focus of this thesis is on the meso scale infrastructure.

Instead of only focusing on traffic accidents, efforts for traffic safety should aim to develop transport culture and living environments in a wider sense (YM 2006). The safety of cycling begins on the (macro) level on the land use and transport networks. Luukkonen & Vaismaa (2013) evaluated the literature and name land use and transport as two of the main ways of increasing cycling safety, the others being cycling infrastructure quality, the amount and speed of motor traffic, traffic behavior and education. As described in the previous chapter, the hierarchical nature of the planning system allows zoning to shape safety of transportation. There should be a clear connection between land use and transportation. The city structure not only allows for routes to be designed further but also produces traffic flows by controlling the need to travel. Dense and mixed land use and shortens travel distances which enables cycling (YM 2006). The mode of choice is affected by the accessibility to (and of) public transit and the availability of parking, both of which are guided with zoning. Emphasis should be on the transport system as whole, considering public transit and motor vehicle traffic, not only thinking about cycling as a separate mode (Vaismaa 2014).

Environment

The environment affecting design includes natural and traffic conditions that are relevant to cyclist safety. In Finland, the climate sets limitations to both cycling volumes and the safety that can be achieved with infrastructure. Cyclists are in the open air with wind, rain and snow which increases discomfort and has an effect on safety. To some extent, the weather conditions can be addressed with maintenance, mainly with snow ploughing, gritting and deicing. Traffic conditions relevant to design are consist of the volumes and speeds that affect cycling safety. Usually the design of infrastructure has a reactive nature in addressing the needs of transportation planning: the solutions (such as traffic calming) that are in the end done with street design elements, need to be feasible in the network scale. Furthermore, they need to follow the intent of the zoning of the area and legislation, as well as the physical limitations of the site and budgetary realities of the municipality.

Albeit the “safety in numbers” is shown on the larger scheme, locally high cyclist volumes are associated with an increased injury risk at intersections (Harris et al. 2013). Then again, Schepers et al. (2017b) found that cycling speeds are lower with increased cycling volumes. There is a similar effect for motor vehicles: an increase in motor traffic
volume decreases injury severity because speeds decrease when nearing road capacity (Allen-Munley et al. 2004). Whether the safety increases, depends on whether the new cyclists are former drivers or public transit passengers. Ideally when evaluating safety, it is important control for exposure and of the road segment before and after there has been infrastructural changes, using controlled before-after method (Thomas and DeRobertis 2013). Without any exposure control the increased volumes might create the false impression that cycle paths decrease safety since they draw in more cyclists on the high traffic volume streets, though the crashes relative to the number of cyclists remain low (Thomas and DeRobertis 2013; DiGioia et al. 2017).

User

A person defined as a cyclist is bicycling, not walking the bicycle. Therefore, falling while walking the bicycle does not constitute a cycling accident (FTIA 2014a, p. 30). Cyclists are considered as vulnerable road users, due to the lack of protection and mass differences between cyclists and motor vehicles. In some ways cycling differs greatly from the other modes. Cyclists riding conventional (muscle powered) bicycles are reluctant to stop and forfeit their kinetic energy. Of all modes, there is possibly the most heterogeneity among cyclists concerning speeds and maneuver abilities. Unlike cars, cyclists are in danger of slipping (same as mopeds and motorcycles). While the use of helmets accounts for some safety (Kaplan et al. 2014), it does not explain low injury risk in countries such as Germany, Denmark and the Netherlands where helmet use is rare and cycling infrastructure is frequently available (Tesche et al. 2012). Improving cycling facilities leads to increased cyclist volumes and to a wider spectrum of cyclists. Increased number of cyclists with elevated risk for accident can manifest as a higher death count, especially on single-bicycle accidents (Schepers et al. 2017a), compared to a situation with poor infrastructure and only cyclists that are able and relatively comfortable to cycle among motor vehicles. Those with elevated risk for death are especially the elderly and young children (Schepers et al. 2017a; Kaplan et al. 2014).

Vehicle

As this thesis is focused on infrastructure, it includes little on the vehicles. The data used in the accident analysis part of methodology includes few electric bicycles, and any such are grouped with regular bicycles. Their effect on safety is not unambiguous and is still researched upon (Schepers et al. 2018; Weber et al. 2014). Similarly, the type of the muscle powered bicycle is not addressed. Though, there might be reason to assume the type of the bicycle has a relationship with the skill level, travelling speed or risk taking of the cyclist (e.g. a shared bicycle compared to a high-quality road bike or mountain bike), it is a subject for another study. The accident data includes virtually nothing on the matter.

The methodology of thesis does not differentiate between motor vehicle types (passenger car, van, truck or bus) with the exception of mopeds that are separated from the data while travelling on cycle path and as motor vehicles while on the carriageway. The safety related to larger vehicles is to some extent discussed on the background. Trucks and vans increase cyclist accident risk (Kim et al. 2007; Vandenbulcke et al. 2014; Kaplan et al. 2014). Due to the mass, it is evident that a larger vehicle with larger mass will account for a higher chance or severity in the case of an injury. Even non-truck accidents on truck streets can increase the likelihood of accidents because of the reduced visibility (Allen-Munley 2004). Larger vehicles also have trouble using intersection waiting areas designed for passenger cars (Cycling Embassy of Denmark 2012). At times mopeds are
allowed on the cycle path with the added sign “allowed for mopeds” (TLA 18 §). Wegman et al. (2012) advice on assigning mopeds on the carriageway instead of cycle tracks. FTIA (2013) and (2014b) include further safety evaluation of mopeds in the urban context.

**Infrastructure**

The level of focus in this thesis is infrastructure design. Although the relationship of cyclist volumes and safety is known, according to a meta-analysis by Elvik and Bjørnskau (2017), it is not possible to prove the causality of “safety in numbers”. Those locations that have a high number of cyclists also have advanced cycling infrastructure, as they are connected. This, however, underlines the importance of not relying only on increasing cyclist numbers but also improving the facilities to achieve safety. According to Kaplan et al. (2014) infrastructure improvements are highly beneficial for cyclist safety, and “safety in numbers” relates to injury severity. Chataway et al. (2014) found in Denmark that infrastructure improvements increase cyclist safety. Luukkonen and Vaismaa (2013) state that cycling infrastructure quality and transport network are the most significant factors in affecting cyclist safety. Similarly, Vandenbulcke et al. (2014) states that though continuity is important, it is better to allocate resources to cycle infrastructure quality rather than on an extensive network of inferior quality. This thesis is addressing the larger scale of infrastructural (street) design than the very detailed aspects that are related to construction and maintenance.

While densifying city structure enables more cycling and walking, and is bound to lead to increased safety, it can pose a challenge to the infrastructure, as there is less available street area to use for intersection treatment and road sections. Since bidirectional paths require much space, unidirectional design can prove safer. The infrastructure design relevant to cycling safety (defined here as meso scale) includes geometrical aspects such as alignment, mode separation and width. Other considerations closely related to traffic environment include signage, street markings, parking, lighting and roadside objects. They affect cycling safety through traffic speeds, volumes, overtaking, visibility, drainage etc., and are addressed to some extent in relation to the design of the intersections. Signal-control is closely connected to infrastructure, but it is a different approach than design in dealing with cyclist safety. Therefore, signal-control is discussed only when it is relevant to unidirectional infrastructure, and where unidirectional solutions fit signalized intersections, while signal phases or cyclist-specific control, for instance, are not covered. The aspects that are distinct for unidirectional design are discussed further in chapter 2.5., mainly the amount of separation and its implications to safety.

In the detailed (micro) scale of infrastructure, according to the city of Helsinki (2019, p. 7), cycling safety problems are the consequence of: surface damage, slipperiness, snow plowing leftover ice and ruts, the location of manhole covers, material selections, construction errors, low-quality restoration and sharp structures that damage the bicycle. Paved surfaces and low-angled grades are additional factors that improve cyclist safety (Reynolds et al. 2009; Allen-Munley et al. 2004). Poor street maintenance increases the risk of cyclist accident tenfold (Dozza and Wernke 2014). Utriainen (2020) studied the Finnish insurance data on single-bicycle accidents and found that 63% of them are related to infrastructure and 14% with avoiding other road users. The infrastructural reasons had either to do with maintenance, detailed design and construction: skidding due to slippery surface, colliding with an object or curb, uneven road surface and (mostly tram) rails (Utriainen 2020).
2.4 Safety of bidirectional cycle paths

Bidirectional cycle paths (BCPs) are segregated cycling facilities, usually shared with pedestrians or separated with markings, which allow cycling in both directions. In Finland, bidirectional shared paths have long been the default way of designing cycling and walking. Thomas and DeRobertis (2013) reviewed literature of the safety of urban cycle tracks and concluded that generally unidirectional cycle paths are safer at intersections than BCPs, and they decrease cyclist crashes with some intersection treatments. Even without any intersection treatment, unidirectional cycle paths reduce injury severity. (Thomas and DeRobertis 2013). Schepers et al. (2017b) name unidirectional cycling among the top three factors for high level of cyclist safety in the Netherlands. CROW (2016) and Cycling Embassy of Denmark (2012) caution against BCPs on urban streets unless they strongly reduce cyclists’ need to cross collector streets.

The main problem with BCPs is that they allow for cyclists to travel to the opposite direction to motor vehicles on the nearest lane, creating unexpected situations, which is shown to increase the risk of accidents and injuries (Räsänen & Summala 1998; Harris et al. 2013; Methorst et al. 2017). Unexpected travel direction, in other words, means that the cyclist is travelling on the cycle track on the left side of the adjacent street, as would not be legal on a unidirectional cycle path. A conflict analysis by Zangenehpour et al. (2016) showed no significant decrease in the probability of interactions with left-sided cycle tracks on signal-controlled intersections, and 40% less conflicts on right-sided cycle tracks, when compared to no cycle facilities. For left-turning motor vehicles, cyclist on the left side is possibly on the blind spot. With right turns the visibility is better, but the differing direction remains, along the fact that the driver needs to also look out for cyclists travelling on the right side. The complexity of an intersection seems to increase risk for cyclists (Räsänen and Summala 1998; Methorst et al. 2017). By removing the unexpected travel direction, unidirectional design simplifies the intersections, leaving them off with fewer conflict points and clearer right of ways. BCPs can increase conflicts between cyclists (CROW 2016). Elevated risk for head-on collision, especially with mopeds, is an issue with BCPs (Methorst et al. 2017), as without bidirectionality the opposite travel direction is located on the other side of the street. Additionally, BCPs can be confusing for pedestrians (City of Helsinki 2016).

The extreme case for cyclists travelling on the unexpected direction is when the driver, approaching the near side of the intersection, is about to turn right and does not pay attention to the cyclist on the BCP coming from the right. Drivers mostly scan other drivers, which might be a result of cyclists posing a small threat to them (Herslund and Jørgensen 2003). Summala et al. (1996) found that drivers about to turn right do not focus their attention to the right as much as left, where the only other motor vehicles that they have crossing travel paths with, are coming. Räsänen and Summala (1998) found that before impact, of motor vehicles turning right only 11% spotted the cyclist coming from the right, while 68% of the cyclists spotted the motor vehicle. CROW (2016, p. 141) cites a Dutch study where more than a quarter of drivers neglected looking at right (only look left) on this situation.

Although Pasanen and Räsänen (1999) found that BCPs are less safe than cycling on the carriageway, results from Lusk et al. (2011) and Zangenehpour et al. (2016) suggest that BCPs have either lower or similar injury rates to no cycle tracks. Kim et al. (2007) found that travelling against the traffic flow (on BCPs) produces a weak U-shaped curve when plotting injury severity: it increases the probability of fatal injury and also the probability of possible or no injury. There the opposite travel directions probably produce both better
visibility (a higher chance of spotting each other) and head on collisions which are more severe (Kim et al. 2007). On road sections BCPs do have the advantage that comes with segregated cycling facilities: protection of rear-end collisions with overtaking motorists.

Bidirectional cycle paths (BCPs) serve a purpose on the cycling network. It is evident for functionality that solitary cycle paths further away from streets (usually shared with pedestrians) should not be made unidirectional. Such remote paths with flow on only one direction would be insufficient on the cycling network. In these cases, there usually is ample space to construct quality BCPs where the directions (and possibly pedestrians) are separated with markings. Accordingly, the greatest cycling cities have BCPs mainly on sections where cycling is not adjacent to motor vehicles (Vaismaa 2014, p. 240). BCPs can be considered if there are few minor streets crossing (Cycling Embassy of Denmark 2012, p. 85). They should be planned when the surrounding network requires it (City of Helsinki 2016). Along busy streets they might be justifiable when the crossing possibilities are scarce, as they can diminish the need to cross, especially when the buildings are on one side of the street (CROW 2016, p. 141; City of Helsinki 2016). BCPs offer greater flexibility when cycling flows are tidal: significantly larger flows in one direction during peak hours. A characteristic of unidirectional cycling design is that it forces cyclists to cross the street when returning to their point of origin. This is inconvenient with short trips and can lead to cyclists disobeying the driving directions. With street sections where services are (and will be) heavily located on one side of the street, it might be better to have a BCP on this side. Design is a compromise and should be reasoned on a case by case basis. BCPs are a recommended solution when the advantages on network scale exceed the lost safety at the intersections (CROW 2016, p. 141).

A quality BCP requires space (City of Helsinki 2016; Methorst et al. 2017). When space on the street area is scarce, unidirectional design is better than insufficiently wide BCPs. In Espoo, with the design paradigm so far, often the BCPs are constructed only on one side of the local collectors and some local streets, and on both sides of regional collectors with multiple lanes. When cycling infrastructure is introduced by adding unidirectional cycle lanes to the side of the street with no cycling facilities, there are less possibilities for shortcomings, as compared to existing BCPs. In the case of Espoo, making changes in the current BCP system might produce at least temporal unwanted results. Cycling infrastructure improvements increase the number of cyclists and thus might seem to decrease safety without the appropriate exposure control. Infrastructural changes require the traffic culture time to adjust, which can make it challenging to conclude whether some design is inherently worse or only unaccustomed to. Conversely, Methorst et al. (2017) studied the hypothesis that BCPs cause safety issues in the Netherlands for this reason: that they are rare and unaccustomed to. Their hypothesis was discarded as implausible with the literature available: BCPs seem to be an inherently safety decreasing design solution (Methorst et al. 2017).

When BCPs are constructed emphasis needs to be placed on visibility, which is in part achieved at intersections by reducing side street motor vehicle speeds, as the forced deceleration gives the drivers time to notice the cyclists. In before-after study by Summala et al. (1996) the drivers’ visual search patterns to the right was increased with raised crossings, speed bumps, street markings, and STOP signs, while colorful cycle paths alone had little effect. CROW (2016, p. 141) advices strongly BCPs crossings to be always built as raised and deflected around 5 meters, for the same reason. For road sections, the width needs to be sufficient to avoid head-on collisions (Methorst et al. 2017).
2.5 Unidirectional design safety considerations

Unidirectional cycling facilities are used on tight urban areas where motor vehicles are present. The main advantage of unidirectional (one-way) cycling is that the cyclists’ unexpected travel directions at intersections inherent to BCPs are removed. There are two definitions for a unidirectional cycle path. The narrow definition includes only cycle lanes and tracks while the wider definition includes also streets with mixed traffic, where cyclists travel on the carriageway among motor vehicles. Unidirectional cycling facilities (Table 2) can be physically separated from motor vehicles (cycle track), from pedestrians (cycle lane) or from both (three-level solution).

<table>
<thead>
<tr>
<th>Design solution</th>
<th>Separation from motor vehicles</th>
<th>Separation from pedestrians</th>
<th>Unidirectional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle lane</td>
<td>Material/mark ing</td>
<td>Physical</td>
<td>Yes</td>
</tr>
<tr>
<td>Cycle track</td>
<td>Physical</td>
<td>Mark ing</td>
<td>Possible</td>
</tr>
<tr>
<td>Three-level</td>
<td>Physical</td>
<td>Physical</td>
<td>Yes</td>
</tr>
<tr>
<td>Mixed traffic</td>
<td>None</td>
<td>Physical</td>
<td>Yes</td>
</tr>
<tr>
<td>Bicycle street</td>
<td>None</td>
<td>Possible</td>
<td>Yes</td>
</tr>
<tr>
<td>Solitary cycle path</td>
<td>Physical</td>
<td>Possible</td>
<td>No</td>
</tr>
<tr>
<td>Bidirectional cycle path (BCP)</td>
<td>Physical</td>
<td>Possible</td>
<td>No</td>
</tr>
</tbody>
</table>

The need for separation comes primarily from differences in speed, size and mass, but also from the maneuverability between different modes (CROW 2016, p. 36). Pedestrians and cyclists are considered as vulnerable modes. There are multiple studies that argue for the safety of segregating cycling from motor vehicles, such as Pucher and Buehler (2008), Harris et al. (2013) and Lusk et al. (2011). These are covered below in detail. Since BCPs cannot be (and never are) joined with motor traffic, the question of segregation between motor traffic and cyclists is between unidirectional mixed traffic or cycle lanes and raised cycle tracks or BCPs. This chapter consists of the safety of design considerations for road sections and intersections when unidirectional solutions are chosen. However, since not all design can be unidirectional, considerations need to accommodate also BCPs. The reasons that decrease safety are present with BCPs, arguably (and depending on the solution) even more so. Therefore, while some design elements are distinct to unidirectional design, the ideas concerning safety are not limited to it.

Separating pedestrians

The old “light traffic” paradigm where pedestrians and cyclists were clumped together (with SCAFT) is being changed, as transport planners are increasingly focusing on walking and cycling. The Ministry of Transport and Communications has dropped this concept and replaced it with “cycling and walking”. Walking and cycling are very different travel modes based on their needs and abilities, and the separation of them is necessary in order to supply adequate solutions for both modes (City of Helsinki 2016). On low motor traffic volume streets, it is better to have cycling on the street than mixed with pedestrians. CROW (2016, p. 127) recommends separating pedestrians when pedestrian volumes require it. Cycling speeds differ greatly from those of pedestrians and are closer to motor vehicles, especially when motor vehicle speeds are desired to stay low because of the type of the traffic environment.
Cycling on shared lanes has been associated with increased odds of injury, albeit not statistically significantly (Harris et al. 2013; Teschke et al. 2012). In Finland, most of the accidents between pedestrians and cyclists occurred on shared paths, which is double to those on separated paths. The accidents and reported dangerous situations are most commonly those where cyclists and pedestrians are travelling on the same direction. (Mesimäki and Luoma 2020).

Cycling on the sidewalk, in turn, is not only illegal and inadequate for transport planning. Lusk et al. (2011) found cycling on sidewalks to increase accident risk by a factor of 1.8. Meta-analysis by Reynolds et al. (2009) concluded that cycling on sidewalk is a factor decreasing safety. 21% of dangerous pedestrian-cyclist encounters in Finland occurred on sidewalks (Mesimäki and Luoma 2020). As unidirectional solutions require less space, they can ensure the proper segregation of pedestrians than with BCPs. The effect BCPs have had on cyclist-pedestrian accidents on shared paths is evaluated on the accident data results in the methodology part of this thesis.

In three-level cycle path the cyclists are physically separated from both motor vehicles and pedestrians with a curb. This is a common solution in Copenhagen (Chataway et al. 2014), while shared track (with pedestrians) is recommended only when there is little space available (Cycling Embassy of Denmark 2012, p. 83). The curb between cyclists and pedestrians needs to be low enough for it not to interfere with cyclists pedaling. Separating pedestrians from cyclists has its perks and challenges which are depicted on Table 3. The separation can be achieved with any of the unidirectional solutions, of which cycle track with only markings has the least separation. Unidirectional considerations between motor vehicles and cyclists are discussed below. The considerations about width and bus stops are relevant also to pedestrians.

<table>
<thead>
<tr>
<th>Perks</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced conflicts with pedestrians and cyclists</td>
<td>Cycling speed increase</td>
</tr>
<tr>
<td>Physical and experienced safety increases</td>
<td>Pedestrian danger increases on crossings and open places</td>
</tr>
<tr>
<td>Increased fluency, especially accessibility intersections</td>
<td>Increased spatial requirements</td>
</tr>
<tr>
<td>Possibility to implement unidirectional cycling</td>
<td>Possibly larger construction costs (dependent on the solution)</td>
</tr>
<tr>
<td>Cycle path capacity increases</td>
<td>Larger maintenance costs and requirements</td>
</tr>
<tr>
<td>Increase in level of service (safety, fluency, accessibility of roads and environment)</td>
<td>Reduced winter visibility with only visual separation (material and road surface markings)</td>
</tr>
<tr>
<td>Walking-related activities improve</td>
<td>Separation not necessarily obeyed if it is not clear and coherent enough, or against custom</td>
</tr>
</tbody>
</table>
2.5.1 Road section design

Road sections and intersections are addressed separately, although there are similarities. Some of the considerations regarding road sections are applicable to intersections and vice versa. Finally, the considerations are brought together on the network scale. While usually intersections are addressed primarily, as most of the accidents occur there, Kaplan et al. (2014) found a higher risk on injury severity on road sections in Denmark. Dozza and Werneke (2014) differentiate between single-bicycle accidents and accidents with motor vehicles at intersections, as they seem to originate from different situations and mechanisms and require different countermeasures. Since single-bike accidents are estimated to be especially underrepresented in the statistics (Destia 2019), the number of them must be considerably higher than what is visible on the data. However, in this chapter, the “road sections” refer to those that are on urban areas and next to streets and have relevance for unidirectional design. Unidirectional design has small chance to improve single-bike accidents or cyclist-cyclist accidents on solitary cycle paths that are not adjacent to the street as they are always implemented as bidirectional (usually shared) paths.

The design of visibility on road sections is a product of street geometry and obstacles on the street area. Street curvature significantly increases injury severity (Kim et al. 2007). With unidirectional design, sufficient visibility is easier to provide, as head-on collisions are limited to those travelling illegally against the flow. The ease of overtaking depends on the cycling and motor vehicle volumes and the quality of the cycle path. With tidal flows there is surely more space for overtaking on BCPs than on unidirectional paths, as the whole width can be utilized at times for one direction.

Mixed traffic

The simplest and most common unidirectional solution is mixed traffic flows: cyclists on the carriageway without any cycling facilities. Though purpose-built bicycle-specific facilities reduce crashes and injuries among cyclists (Reynolds et al. 2009; Harris et al. 2013; Lusk et al. 2011), they are not needed on low traffic streets, mainly on local streets. City of Helsinki (2016) recommends cyclists to be segregated where motor traffic speeds or volumes cannot or should not be controlled, and conversely, motor traffic volumes and speeds are to be controlled there where cyclists cannot or should not be or segregated. Pasanen and Räätänen (1999) found that cycling on the carriageway is safer than on BCPs, based on the accident data from Helsinki in the 1990s. Mixing different modes can increase safety by increasing the visibility between them and makes the drivers focus on cyclists (Herslund and Jørgensen 2003). Teschke et al. (2012) found local streets without cycling facilities as among the street types with a reduced risk of accident. Well-organized local streets do not need cycle lanes for safety, but they might need them for functionality of the cycle route (CROW 2016, p. 114). However, Pulugurtha and Thakur (2015) and Cycling Embassy of Denmark (2012, p. 51) deem cycle lanes generally a safer solution than mixed traffic.

Urban street width reduction could result in a safer traffic environment for all road users (Schramm and Rakotonirainy 2009). A tight width profile on a mixed traffic street forces motorists to follow the speeds of the cyclists, and is recommended when both volumes are lower, a wider profile tempts motorists to higher speeds, which can be prevented with additional speed-reducing measures (CROW 2016, p. 106). Cyclists on the carriageway can calm motor traffic speeds. Mixed traffic solutions are very easily joined longitudinally to unidirectional cycling facilities (City of Helsinki 2016). A special case of mixed traffic is the bicycle street where motor vehicles are allowed to travel but the speed limit...
is very low. Keeping mopeds away from urban cycle paths has been associated with increased safety, as the municipalities that have removed “mopeds allowed” added signs from cycle paths have had decreases in accidents (FTIA 2013).

**Cycle track and cycle lane**

Whether to construct cycle lanes on the side of the carriageway or to raise them is a question of separation (Figure 5). There are multiple studies that associate segregated facilities with increased safety. The foremost way of increasing road section safety is mode separation (Wegman et al. 2012). CROW (2016, p. 108) recommends by default cycle tracks to be preferred, because of the increased safety and decreased emission exposure. Harris et al. (2013) found cycle tracks considerably safer on road sections than cycle lanes. Morrison et al. (2019) found that overall, exclusive cycle tracks are associated with reduced crash odds for all street segment characteristics.

![Figure 5 Raised cycle track (NACTO 2014). This is a variant of the three-level solution with recessed cycle path.](image)

On road sections, cycle lanes compared to BCPs have the advantage of unidirectional design, that is reduced head-on collisions (ITF 2013). While segregated facilities seem the safe choice, often they are not feasible, due to spatial or budgetary reasons. For unidirectional design the question of cycle lane safety is rather whether cycle lanes are better than cycling on the carriageway. The safety effects of cycle lanes are mixed, but overall positive as compared to no facilities. Meta-analysis by Reynolds et al. (2009) found cycle lanes to have consistent positive effect to cyclist safety on many studies in North America. They concluded that clearly marked cyclist specific facilities increase safety (including cycle tracks), as opposed to cycling on the carriageway. Mulvaney et al. (2015) found no conclusive evidence in 20 before-after studies that cycle lanes (or tracks) reduce or increase the rate of cyclist collisions. Kaplan et al. (2014) found little difference on minor or severe injuries but a strong relation to the reduction of a probability of fatal accidents on cycle lanes, when compared to no facilities. Pulugurtha and Thakur (2015) found that sections with cycle lanes have lower risk of accident (from a third to a quarter depending on the traffic conditions) than on sections without lanes. They also found no significant negative consequences with installation of cycle lanes. Also Chen et al. (2012) found no significant increase in crashes after introducing cycle lanes, though probably cycling volumes increased. In a before-after study by Jensen (2007) cycle lanes worsened safety of both on road sections and intersections. Cycle lanes have resulted in a significant accident
reduction on road sections but also increased accidents at intersections (Cycling Embassy of Denmark 2012, pp. 65).

The construction and maintenance costs depend on the design solution. Cycle track construction costs can match those of cycle lanes, depending on which side of the curb the excess space can be taken when the street is renovated. A raised cycle track constructed on a new street can be less expensive than a cycle lane (NACTO 2011). If the space for the cycle lane is taken from the carriageway no renovation is needed, since the cycle lane can simply be painted on the side of the carriageway with little costs. Cycle lanes have little added maintenance costs as the paint does not wear down excessively from motor vehicles that do not travel on it, except when turning over it. Painted cycle lanes can work as a temporary solution while waiting for the resources to construct separated cycle tracks, as long as the required width is the same (Cycling Embassy of Denmark 2012). The budgetary considerations are explored further in the project related to this thesis.

The highest level of service solution, three-level separation is the most expensive to construct and maintain. In construction the street strip requires double the number of curbs. The inclinations might need further planning and constructing than on a simpler two-level solution. For maintenance, snow plowing needs to include extra rounds compared to a two-level solution. The highest quality solution of three-level is with the inclination on the cycle lane away from the carriageway, thus placing cyclists on the same level of motor vehicles and minimizing the bumps at intersections. This will, however, often require a separate drainage for the cycle tracks, which can be a costly solution.

Protected cycle track

Protected cycle track is a special case of the cycle track where the separation from motor vehicles is not limited to the curb. Protection can be achieved by using the space reserved for equipment on the street area: placing the cycle track on the sidewalk side of the separation lane that is used for signage and as a snow area. Commonly vegetation is placed on the separating verge. Obstacles must not obstruct visibility to the cycle path before an intersection. With the separation verge, the cycle path does not need to be in a different level than the carriageway, though it might need to be separated from the sidewalk. Physical barriers used in some countries between cyclists and motorized traffic, such as flower installments, fences or poles, are sure to increase cyclist safety, but in the Finnish climate the maintenance can become a problem. It is common knowledge in the field of street design that fences should be avoided for the maintenance reasons. A pole line separating the cycle lane is the equivalent of a fence. Snow plowing is difficult near the pole line, and moreover the vehicle does not fit inside to plough the cycle path itself. The use of smaller specialized equipment introduces evident operational challenges.

Having only a curb in between does little but wider disentwining (such as three-meter separation lanes) can make a difference to the emissions reaching cyclists. This a reason why CROW (2016, p. 103) recommends constructing cycle tracks instead of lanes, whenever possible. On a wider scale, increasing cycling safety can increase cycling volumes and thus reduce the number of motor vehicles that produce the emissions.

With moderate urban speeds, road section safety is not affected by deflection as much as intersection safety. However, the question arises with on-street parking and bus stops. There are two issues with bus stops and cycle paths. Buses on cycle lanes can resolve in conflicts when they are lining up with cyclists, and cyclists can collide with pedestrians.
getting on and off buses. Alternatively, the cycle track can be placed on the pedestrian side. Jensen (2007) found an increase in cyclist-pedestrian accidents on bus stops when introducing cycle tracks. A sufficiently wide waiting platform or deflected cycle path ensures pedestrians have a place to wait while getting on or off the bus (CROW 2016, p. 122; Cycling Embassy of Denmark 2012, p. 85). Designing bus stops in this manner makes the cycle path in effect a protected cycle track. With unidirectional path the flow of cyclists would be only on one of the directions, which is bound to increase the safety of pedestrians.

**Dooring**

According to some sources, dooring accounts for 12-27% of urban bicycle-motor vehicle crashes (Schimek 2018). The first recommendation to prevent dooring is to not place parking on sections with cycle lanes, or vice versa (CROW 2016, p. 110). To the advantage of cyclist safety, the protected cycle track is shifted to the pedestrian side of an on-street parking lane, as is often the case in the design of Copenhagen (Chataway et al 2014). This provides an evident protection from the traffic on the carriageway. In this case the cycle path would usually be implemented as a (raised) track to prevent parking on the cycle lane. Though this will reduce the occurrences of dooring since the driver’s side door is opened at every parking and the passengers’ side only when there are passengers, a buffer is be needed. When possible, street signage should be assigned on the right side of the cycle path (City of Helsinki 2016). Neither parked cars nor bus stops should be located right before an intersection for cyclist safety (Cycling Embassy of Denmark 2012).

When this is not possible, dooring can be mitigated by two ways related to infrastructure: ensuring adequate space to safely avoid open doors by aligning the cycle lane to some distance from the parked vehicles or by separating it physically (Johnson et al. 2013). These solutions require space on the street area. For ordinary cycle lanes next to on-street parking a 75 to 90 cm buffer zone is recommended as a countermeasure against dooring (City of Espoo 2010; City of Helsinki 2016; Schimek 2018; Vandenbulcke et al. 2014). The buffers can be made with pavement markings, disentwining the cycle lane, material differences or raising the parking lane.

Sharrow are markings used on the street that indicate the cyclist’s place. They are placed some distance from parked cars next to the carriageway, mainly to avoid dooring. They are a minor solution that could have some benefit on a low volume street, but the effect of sharrows to cyclist injury has been similar to plain mixed traffic street, that is negative (compared to segregated facilities), though not statistically significant (Harris et al. 2013).

Dooring is a possibility only when there is ample space to have on-street parking as well as separate cycle paths. Commonly when space is scarce the choice is to construct either one or the other. The worst decision is to paint too narrow cycle lanes on the street side of the parking lane. Recent accident data review from Helsinki showed 24 dooring accidents, which was around 1.5% of all cycling accidents (Härme 2018, p. 24). Currently, dooring does not appear to be a problem in the case of Espoo, as the accident data from 10 years included virtually no doorings. This is not to say doorings could not emerge when cycle lanes are introduced.
Lane or track width

As with any design, the quality of the cycle lanes or tracks affects the results: having too narrow cycle lanes or located on too high volume or speed traffic affects poorly on safety. While a wider carriageway produces higher motor vehicle speeds and increase dangerous and illegal overtaking (Allen-Munley et al. 2004), similarly, too narrow carriageway adjacent to cycle lanes decreases safety of the cyclists, though the width of the carriageway has less effect on safety on urban areas (Cycling Embassy of Denmark 2012). The width of the carriageway for cycle lanes should be at least 5.8 meters (CROW 2016, p. 119).

Cycle lane width relates positively to the passing distances, as too narrow cycle tracks can produce difficult overtaking and decreased safety (Cycling Embassy of Denmark 2012, p. 51). Insufficiently wide cycle lanes (1.45 meters) have produced overtaking with smaller passing distances than on a street without any cycle lanes, on high speed locations (~65-80 km/h). The results were not significant on streets with lower speeds. (Parkin and Meyers 2010). Sufficient width of a cycle lane is associated with safety (Pulugurtha and Thakur 2015). When the speed of motor vehicles is high, the cycle lanes need to be wide (minimum of 1.70 meters) in order to be safe and comfortable (CROW 2016, p. 119).

Cycle path width is affected by the function of the cycle path and the street: more cycling volume requires more width. Overtaking and cycling two-abreast affects the design width. (Yan et al. 2018). Cycle lanes do not need to be as wide as segregated tracks since cyclists can momentarily borrow space from the carriageway (for instance when overtaking). Cyclists on the raised cycle track, however, cannot use the pedestrian side when overtaking, as legal and safe overtaking is done from the left side (TLL 2018/729, 31 §). With raised track, there is also the possibility of falling. Though generally infrastructural solutions are desired to be somewhat uniform throughout road sections, cycle path width can vary depending on the conditions on the street, such as parking, obstacles, uphill stretches, as well as the used bicycle types. Required width depends on whether they dimensioned for cargo bikes or regular bikes. Although cargo bikes are rare, they can create bottlenecks for cycling flows if the facilities are not planned for them. Uphill stretches require more width because of the increased difficulty in maneuvering. Downhill gradients on the other hand increase risk of cyclist injury on both intersections and road sections (Harris et al. 2013; Teschke et al. 2012). Increasing cycle lane width increases cycling speeds (Greibe and Buch 2016). Too narrow cycle tracks can also make cyclists travel on the sidewalk (Cycling Embassy of Denmark, p. 83).

Cycle lanes can be buffered to separate them further from the adjacent motor traffic with sufficiently wide markings. The quality of the cycle path affects the effectiveness of the width, since the better the path is defined the closer to the edge cyclists are positioned (Greibe and Buch 2016). The recommended widths for unidirectional paths range from 1.50 to 2.50 meters, depending on the said conditions (CROW 2016, p. 111; Yan et al. 2018; NACTO 2011, p. 81; Greibe and Buch 2016, p. 134).

Contraflow cycle lanes

Contraflow cycle lane (Figure 6) is a solution which allows cyclists to travel in the opposite direction of motor vehicle traffic by converting a one-way street into bilateral: one direction for motor vehicles and bikes, the other for only bikes (NACTO 2011, p. 31). Unmodified one-way streets are by default not safer for cyclists, even though they have a lower number of conflict points, as they often have wider lanes which increase motorist
speeds, and they can make cyclists travel in the wrong side of the street and be less cautious when turning (Allen-Munley et al. 2004). On the surface, contraflow cycle paths appear to undo the benefit that is achieved by unidirectional cycle paths: directing cyclists on the opposite directional flow than motor vehicles. However, according to a spatial crash risk analysis by Vandenbulcke et al. (2014), contraflow cycling reduces accident risk. ITF (2013, p. 177) cites a before-after study on Paris, where contraflow cycle lanes introduced to one-way motor vehicle traffic (speed limit 30 km/h) reduced motor vehicle speeds and cyclist accidents even while increasing the cycling volumes significantly.

Contraflow cycling is a solution made practical with the 2020 Road Traffic Legislation. It can be implemented by allowing cyclist travel on both directions of a one-way street with signage, as described in chapter 2.2. However, doing it safely requires some infrastructural changes, such as painted cycle lane on at least to the side of the street that is opposed to motor vehicle flow. As of now, there are not many one-way streets in Espoo, but contraflow is an option when constructing new streets or repurposing existing ones.

Left-sided cycle lane is an exceptional solution where one-way streets or two-way median divided streets have unidirectional cycle lane on the left side of the street (NACTO 2011, p. 46). It does not cater for the problems arising from illogical cycling directions or the consistency of the infrastructure. The purpose of left-side bike lane is to offer advantages along streets with heavy delivery or transit, frequent parking, freeway ramp, on the right side, or other conflicts associated with right-side cycle lanes. Another reason is a significant number of left-turning cyclists. (NACTO 2011, p. 46). In Finland, the cycle lanes are always going on the same direction (or as contraflow) with the motor vehicles, and legislation does not enable left-sided solutions.

2.5.2 Intersection design

The wider definition of an intersection, that is used on this thesis, includes intersections with any two vehicles. Though, cyclist-cyclist accidents on solitary paths are of little importance for the purposes of this thesis. Locations where a cycle path or cycle path extension crosses a street (without the option to turn) are by definition not intersections but crossings. Crossings in proximity of intersections are, however, classified as intersections on the methodology (and on the official accident statistics), as they are seen as part of the intersection. The legislation is not entirely clear on the exact distance that a cyclist crossing must be to constitute as a solitary path (not adjacent to the street). The border is somewhere between 15 to 40 meters (FTIA 2014a).
Although the interchange of traffic flows is not something that could be avoided, proper intersection design can reduce accident occurrence and severity. Most collisions occur at intersections (CROW 2016, p. 67), also in Espoo (described in chapter 4.1). Addressing intersections has the highest potential for increasing cyclist safety, as they increase the bicyclists’ risk of experiencing a critical event fourfold (Dozza and Werneke 2014).

The foremost ways of attaining safety at intersections are ensuring proper visibility and controlling traffic speeds, of which the latter is the most dominant in reducing cyclist risk of accident and injury severity (CROW 2016, p. 135). Visibility between cyclists and motorists approaching intersections is important for safety (Vandenbulcke et al. 2014). Reduced visibility at intersections increases risk of accident twelvelfold (Dozza and Werneke 2014). Reducing motor vehicle speeds is paramount at intersections (Wegman et al. 2012) and associated to increased safety and decreased injury severity (Harris et al. 2013; Kim et al. 2007).

There are multiple ways to control motor vehicle speeds and provide visibility. The ones addressed in this thesis are described below, mainly whether to raise or deflect the cyclist crossing and the effect of paintings and markings. It should be noted that not all of the results found in the literature were with unidirectional paths in particular. Moreover, the differing local conditions make the results difficult to apply to a different location. The design is differentiated on street class and whether cyclist was approaching from major or major street, which is used by Schepers et al. (2011). As minor and major streets have different functions, different means are used to address them. Emphasis should be on visibility from the minor to the major street, especially to the right (CROW 2016, pp. 137, 142; Pedler and Davies 2000; Summala et al. 1996). Unidirectional design alone can solve some of the issues of visibility, as (most) cyclists are not coming from the right.

**Deflection**

Deflection (bending out) of the side street cycle track extension (crossing main street) is common, and it creates little disturbance on the flow. There are no extra cost or spatial requirements to simply offset the painted crossing slightly further away from the intersecting side street. Moreover, the offset is often necessary to provide enough space to turn at the intersection and wait without disturbing the crossing. There is a smaller chance of decreased visibility to crossing the major street that is by definition wider. Henceforth the “deflection” referred to in this thesis means deflection of the cycle path adjacent to the major street.

As for deflecting the cycle path along the major street, the question is slightly different, and there are two effects to safety. On one hand, it is safer to minimize the distance between cyclist and motor vehicles. Thomas and DeRobertis (2013) concluded from the literature that bringing the cycle track close at intersections increases safety. They cited early studies (Leden 1990 and Linderholm 1992) who recommend the cyclists should be brought from the cycle tracks to the carriageway before the intersection (with additional means such as grade separation, bicyclist signal control and stop lines). They cited also Herrstedt et al. 1994 who found that bringing the cycle track close to the parallel carriageway at the intersection improves visibility, but afterwards it can be taken to a distance to give the road users time to react. Richter and Sachs (2017) recommend the cycle track to be kept near the right-turning lane to avoid obstructing the view to the cyclist. Geometry dictates that with some deflection adequate visibility can be harder to manage, as the cycle track is closer to the obstacles on the side of the street. Moreover, the separation lane can
have obstacles which obstruct the visibility. City of Helsinki (2016) recommends unidirectional tracks to be designed usually next to other modes at intersections to improve the interactions and prepare the road users. They can be deflected inwards from a protected track if the speed limit is 50 km/h or less. (City of Helsinki 2016).

However, adequate outward deflection not only gives the road users time to react but also creates a waiting area for the vehicles entering and exiting the major street, and thus sequences the conflicts. Schepers et al. (2011) found that bicycle crossings on unsignalized intersections are safest when deflected 2 to 5 meters from the major street carriageway (and raised). The deflection is important with very severe crashes with right-turning trucks (Schepers et al. 2017b). Also Pucher and Buehler (2008) recommend for deflecting the cycle path at intersections to avoid collisions on right-turning vehicles. Pedler and Davies (2000) emphasize the deflections effect for increasing visibility to the right. A deflection of 5 meters for the major street cycle track is recommended by CROW (2016, pp. 134-135), as it creates a waiting room and removes cyclists from the blind spot of the turning vehicles. Cycling Embassy of Denmark (2012) recommends a deflection of 5 to 7 meters on major dense traffic streets, unless the side road is used often by lorries which cannot utilize the waiting area. FTIA (2014a, pp. 88) presents different possibilities regarding deflection: either bringing the cycle path close or recessing the cycle path to a cycle lane to provide visibility, or to deflect it 2 to 6 meters for the waiting area. City of Helsinki (2016) recommends deflecting cycle paths away 5 meters, if the speed limit is 50 km/h or more, the intersection is on a suburban main street or regional collector or if the main street has considerably larger vehicle traffic turning right while cyclists are going straight (on signalized intersections). As with protected road sections and bus stops, deflection at intersections can provide pedestrians a waiting area.

Even though unidirectional design solves the problem of cyclists coming from unexpected directions, turning vehicles remain. Right-turning vehicles produce a risk for cyclists travelling on the same direction, especially with trucks and lorries. These accidents are rare but very dangerous (Richter and Sachs 2017). Since unidirectional design assigns the cyclists to the right side of the street, it might increase accidents with vehicles turning right and cyclists on the blind spot. Special attention is needed with intersection treatment. In addition to deflection (described above), the problem with right-turning vehicles and cyclists travelling on the same direction can be addressed by raising the cycle path. The question of separation for the cycle track is addressed below. When there is deflection (or separation) between the cycle path and the right-most lane, it should be designed so that obstacles, such as vegetation or traffic control devices do not obstruct the visibility.

Madsen and Lahrmann (2017) found that on signal-controlled intersections a separate right-turning lane seems to be safer for cyclists than a lane where the motor vehicles can also go straight. This might be because the intersections with right-turning lanes have more right-turning vehicles which then results in a relatively low risk (Madsen and Lahrmann 2017). Another explanation would be that the with the separate turning lane, the oncoming turn is expected by each road user.

Left-turning motor vehicles increase risk of conflict for cyclists probably because the low capacity of left turning vehicles force them to cross the intersection at small time gaps, and their visibility might be blocked by vehicles travelling straight (Madsen and Lahrmann 2017). With unidirectional design, left-turning motor vehicles will not have cyclists travelling on the same direction and approach the crossing in the driver’s blind spot. They
will, however, deal with the cyclists travelling in the opposite direction. Deflection will provide a waiting area for the left-turning vehicle and sequence the conflicts.

In the Dutch style protected intersection, the problem of visibility is resolved with the physical elements that force drivers to turn right before coming in contact with the cyclists, and thus seeing the cyclist travelling alongside them, while providing a waiting area. This is essentially what deflection does. Waiting areas are provided also to cyclists going straight. Protected intersection is easily continued from protected cycle paths on road sections, when the alignment of the parking lane or separation lane continues as the protected element (Figure 7). If there is no parking lane, the cycle lane should be gradually aligned to ensure the fluency of cyclists’ flow, though this requires some space from the street area, and at times cyclists need to be slightly slowed down for safety reasons. The realignment can be planned for the motor vehicles, for not to disrupt cyclists travel. Though, deflecting the cycle path can be used to reduce cyclist speeds when approaching the intersection, which is sometimes needed to avoid severe injuries (CROW 2016). Schepers et al. (2017b) concluded that low cyclist speeds are among the top risk factors contributing to the high level of safety of the Netherlands (among motor vehicle speed-reducing measures and unidirectional cycling). The protected intersection is applicable to both unsignalized and signalized intersections, where the cyclist right turn is free (can be done with a red light).

![Figure 7 The principles of a protected intersection. The crossing setback (waiting area) is recommended to be constructed as 6 meters wide. (Gilpin et al. 2015).](image)

The protected intersections have increased in popularity in the United States. They provide more reaction time and correct for mistakes due to lowered speeds, though pedestrian safety needs to be considered (Gilpin et al. 2015). A deflected cycle path can be raised. Deflection requires additional space from the street area, and it might be difficult to achieve on all locations. As coherence of design is important, this brings in the question
of how much deflection should be done on the locations with adequate space. Additionally, deflection can be necessary when joining structures that require it. The protected intersection relies on physical separation blocks on the turns, which create a need for specialized snow removal and sweeping (Gilpin et al. 2015).

**Cycle track and cycle lane**

Similarly to road sections, intersections with raised cycle tracks or recessed cycle lanes have different effects on safety. The same general principles apply here as well. Physical (vertical) separation forces the driver to slow down even without spotting any cyclists. Segregation of vehicle types should not be restricted to road sections (CROW 2016, p. 67). A raised crossing can be either a cycle track that continues over the intersection or a cycle lane that is raised momentarily to secure safe crossing, along with a raised sidewalk for pedestrians. Grade-separated facilities completely eliminate conflict with motorized traffic but are often not feasible (CROW 2016, p. 135). Raised crossings need to be in line with the functionality and right of way of the streets. Raising the cycle path is relevant for major streets crossing minor streets or with two equal streets. Unidirectional cycle track (with a 2 to 5 meter deflection) is safer than a cycle lane on unsignalized intersections (Schepers et al. 2011). According to a study by Gårder et al. (1998), raising urban cycle tracks at intersections by 4 to 12 cm increases the safety of cyclists by 30%. Morrison et al. (2018) found separated cycle facilities to increase safety for all intersection characteristics. Raising the cycle track (along with the adjacent sidewalk) also improves safety for pedestrians and motorists (Gårder et al. 1998). Cycle paths should be raised at intersections between two collectors (or use signal-control or roundabouts with denser traffic). If the cycle path continuing through the intersection is not raised, the safety of the cyclists on the major street can be improved by adding a speed bump to motor vehicles approaching from the minor street. (CROW 2016, pp. 135, 146).

While raised cycle tracks at intersection area are shown to increase safety, this is often not feasible for the traffic flow. The safety effects of cycle lanes are mixed also at intersections. Kondo et al. (2018) found in spatial model that compared to no cycling facilities, cycle lanes reduce crash odds by 40-48% depending on the intersection type and traffic volumes. The greatest reduction was on streets with 4-exit intersections, while on signalized or 3-exit intersections they made no difference (Kondo et al. 2018). A before-after meta-analysis found that continuing a cycle lane across the mouth of a side road (with markings) may increase the risk of injury, though the results are not certain (Mulvaney et al. 2015). Jensen (2007) found in a before-after study inserting blue cycle lanes (Figure 8) having a 15% of increase in injuries. However, the study found decreased safety also when constructing raised (unidirectional) tracks, and the results varied significantly with locations. Jensen (2008) repeated the study on 65 signal-controlled intersections and found a statistically significant improvement in cycling safety with 10% reduction in accidents and 19% in injuries. The lines should be used on one mouth of an intersection, since too many seem to attract too much focus on cyclists and decrease overall safety. Adding blue markings to both sides of the street had a 23% increase in accidents and a 48% increase in injuries. The blue crossings had the greatest positive effect on smaller signalized intersections, and possible negative effect for complex intersections. (Jensen 2008).
Continuing cycle lanes (marked with blue) through the intersection is recommended with small amounts of traffic on the minor street (Cycling Embassy of Denmark 2012). The continuous cycle lanes calm motor traffic entering from the side streets and emphasize the right of way of the major street. Traffic turning away from the major street should be compelled to slow down. Raising the cycle track over the minor street (along with deflection of 5 to 7 meters) is recommended when there is much traffic on the major street. (Cycling Embassy of Denmark 2012). CROW (2016, p. 143) recommends cycle lanes (or tracks) alongside collectors to be continued through the intersection, with an emphasis for the deflection if the waiting areas are needed. On rare instances, such as downhills grades, the cycle track can be shortened when coming to the intersection, so that cyclists and drivers merge (Cycling Embassy of Denmark 2012). If cycle lanes are not designed, Pulugurtha and Thakur (2015) recommend widening the right-most travel lane to increase cyclist safety. Cycle tracks should not be joined to carriageway on signal-controlled crossings with no right-turn lanes, as they pose major safety problems (Jensen 2007).

Appropriate markings along with signage can increase safety and right of way clarity. Reynolds et al. (2009) found clearly marked solutions to increase cyclist safety as opposed to no facilities. Cycle lanes should be accompanied with markings to have a positive effect on safety (CROW 2016, p. 114). Colored bike facilities can increase the visibility of cyclists, promote the multi-modal nature of a corridor and discourage illegal parking on the cycle lane (NACTO 2011). Colored facilities also highlight the give-way regulations of a cycle path (Cycling Embassy of Denmark 2012). Gärder et al. (1998) recommend painting the (raised) cycle tracks along intersections. However, the benefits of colored facilities are mixed and can be negative for safety (Thomas and DeRobertis 2013). Schepers et al. (2011) found that red color and high-quality markings have an adverse effect on safety: they increase crashes where cyclist is travelling on the priority street (motor vehicle on the secondary street), and even more so on cycle tracks as compared to cycle lanes. Markings seemed to have a greater effect than color. (Schepers et al. 2011).
According to Madsen and Lahrmann (2017) the use of staggered stop lines may contribute to cyclist safety on turning vehicles, though the results are not certain. With cycle lanes on signalized intersections, bike boxes (advanced stop lines, Figure 9) provide a head start and visibility for cyclists and can improve cyclist safety (Pucher and Buehler 2008; Chen et al. 2012). Advanced stop lines are an especially important countermeasure for trucks turning right (ITF 2013). A before-after study of 10 signalized intersections found bike boxes to reduce conflicts between cyclists and motor vehicles, even though the number of right-turning vehicles increased (Dill et al. 2012). Also Thomas and DeRobertis (2013) recommend advanced stop lines, when the crossing cannot be raised. If the cyclists’ access to the bike boxes is not ensured, it can create problems (Vaismaa 2014). Bike boxes can, though, cause problems with cyclists’ left turns and lorries that do not have visibility on the waiting cyclist (Cycling Embassy of Denmark 2012).

Figure 9 An advanced stop line (bike box) improves cyclist visibility on signalized intersections with cycle lanes (NACTO 2014).

NACTO recommends lowering and joining the cycle track to the carriageway and shifting its place with the right turning motor vehicle lane. The solution is recommended as less expensive than a one with bicycle signal-control (NACTO 2011, p. 191). This mitigates issues with the right-turning motor vehicle by increasing visibility and will also sequence the conflicts. Though it introduces a new longitudinal conflict with the shifting lanes, which often have cyclist on the blind spot of the driver. This is not recommended on the Dutch or the Danish practice, though these solutions have been used.

There is a number of additional means of improving safety that are not inherent to unidirectional design. For instance, traffic diverters on local streets (Harris et al. 2013) and improved street lighting are associated with increased cyclist safety (Reynolds et al. 2009), while darkness increases injury severity (Kim et al. 2007). Signal-control is necessary for larger intersections (or roundabouts in some cases) for both safety and fluency. Additionally, the safety issues of right turning vehicles can be reduced with other ways, such as enforcing the yield with signage, with intelligent solutions such as the Amber light that signalized right-turning driver of an approaching cyclist, or by simply prohibiting right turns for motor vehicles. Some of the measures, such as bike boxes and cyclist-
specific signal control are only suited for signal-controlled intersections. Tamminen (2018) studied on how to cater for cyclists on signal-controlled intersections in Espoo.

The most severe injuries for cyclists occur when the cyclist is turning left, and when both parties going straight (Kaplan et al. 2014). City of Helsinki (2016) and CROW (2016) have design sheets for multiple specific ways in which different cycling facilities join safely at intersections, and how to accommodate with the cyclist turns, mainly the difficult left turn. Cyclists’ left turns are dependent on the size and control of the intersection: they can occur through smaller intersections (with advance stop lines), and in two stages of larger (signal-controlled) intersections (CROW 2016, p. 134).

**Roundabouts**

The effects roundabouts have on cyclist safety are somewhat mixed. Roundabouts are a recommended solution safety-wise because they reduce the number of conflict points and approaching speeds (Wegman et al. 2012). They prevent encounters between oncoming traffic, simplify conflict situations by making the conflicts more longitudinal, which are usually less serious compared to lateral ones and reduce speeds (CROW 2016, p. 135, 147). Jensen (2017) found a decrease in the number of injuries and their severity, especially on high speed limits, although the effect on cyclists was negative. Mulvaney et al. (2015) found that generally conversion of intersections to roundabouts may increase cyclist collisions. Daniels et al. (2009) found that generally roundabouts increase the number of cyclist severe injury crashes, regardless of the design type of the facilities. Jensen (2017) argues for the effect roundabout design has in increasing safety.

The location of the roundabout matters. Harris et al. (2013) found that small roundabouts increase cyclist injury risk on otherwise safe local streets. Also the type of the intersection that is replaced with a roundabout matters: signal-controlled intersections replaced with roundabouts have worse effect on safety than unsignalized ones (Daniels et al. 2009). With low traffic volume and 30-50 km/h speed limit, cyclists should mix with motor traffic on a one lane roundabout (Cycling Embassy of Denmark 2012, p. 99). Roundabouts with cycle lanes perform worse than other design types (Daniels et al. 2009; Reynolds et al. 2009). Transforming intersections to roundabouts with cycle lanes increased accidents (Mulvaney et al. 2015). Cycle lanes on roundabouts may be used by motorists to drive faster and they should be used with caution (Cycling Embassy of Denmark 2012). The speeds of motor vehicles can be lowered with speed limits on the arms of the roundabout and equipping the roundabouts with high central islands with wide diameters of 20-40 meters (Jensen 2017).

Separate cycling facilities should be included on the roundabouts to avoid increasing cyclist crash risk, especially on multi-lane roundabouts (Reynolds et al. 2009; Jensen 2017; Mulvaney et al. 2015; CROW 2016, p. 147). With major roundabouts unidirectional track should be positioned 5 meters around the carriageway and right of way should be made clear (Cycling Embassy of Denmark 2012). CROW (2016, p. 148) strongly recommends avoiding BCPs on roundabouts. Cycling facilities in Finland are mostly done with separated BCPs. In Finland, the most common motorist-cyclist accident on roundabouts was when the motorist was leaving the roundabout, and the cyclist was coming from the left (opposite to motor vehicle flow) (Kuittinen 2017). However, when approaching the roundabout, the cyclist coming from the left (same direction as motor vehicle flow) was more common than from the right (Kuittinen 2017).
Unwanted behavior

Informal right of way behavior is an evident risk to cyclist safety that can be affected with design. It is caused by presupposed distribution of main and side roads that are enforced by the difference in spatial quality, that is the characteristics of the traffic and street area. Uniformity and limited number of street categories will increase safety and clarity. (CROW 2016, p. 140-142). Cycling Embassy of Denmark (2012) recommends continuing the cycle track along major streets through the intersection when the traffic volumes are low on the secondary street. This enforces the right of way of the main street. Deflection can be used to make cyclists aware of yielding (City of Helsinki 2016). When cyclists have no priority the right of ways cause least confusion, though these are not necessarily the safest design solutions (Pedler and Davies 2000). As with unidirectional design cyclists travel along motor vehicle flow, it can simplify the right of ways and decrease informal right of way behavior that other traffic environment might produce.

In the Netherlands, the share of cyclist travelling contraflow has been measured locally to be between 0 and 13%, varying with time and place: high traffic volumes seem to correlate with less contraflow with only a few percent on weekdays (Methorst et al. 2017). This is explained with higher cyclist volumes not only forcing cyclists to their correct paths but also showing which way it is. As is with right of way, unwanted contraflow on the cycle path is minimized with cycling volumes, infrastructure and street design, signage and traffic culture. By increasing cyclist volumes and letting the cyclists adjust to the new design, the problems are bound to be reduced to some extent over time.

2.5.3 Network planning

The new transport paradigm is to design cycling (as well as walking) infrastructure in its own baseline instead of as a part of motor vehicle network (FTIA 2014a, p. 12). However, for unidirectional cycling infrastructure, network scale planning is a part of the motor traffic network since unidirectional paths rarely diverge much from the street. The aim of planning is to find a balance between the routes, transport functions and physical solutions (City of Helsinki 2016). Unidirectional cycling is mostly recommended on the dense city street network where there is not enough space to implement quality BCPs (City of Helsinki 2016). Ensuring continuity of routes is very important, but it can be difficult to achieve on lengthy strips on an existing network that was designed for motor vehicles.

When separating cyclists from motor vehicle traffic it is almost inevitable to use an area-wide approach and to relate the infrastructural planning to the nature of bicycle trips (Wegman et al. 2012). When planning routes, unidirectional cycling should not increase the need to cross or travel illegally against the flow, which decrease safety. To prevent this, some additional crossings need to be constructed (where there is only one for both directions of the BCP). One reason for increased crossing is buildings located heavily on one side of the street. Not all of the network can or should be unidirectional, as BCPs offer certain advantages in route selection, which were discussed on the previous chapter. Route consideration is key to planning continuous and safe solutions and finding out when BCPs are required.

As for street functionality, unidirectional cycle paths should be planned along major streets with high motor traffic volumes and speeds (Cycling Embassy of Denmark 2012). Spatial analysis by Morrison et al. (2019) suggests that the relative risks of cycling facilities are not uniform but vary according to specific local conditions. Cyclists are more susceptible to crashes on high speed/high traffic volume multiline streets (Pulugurtha and
Thakur 2015). Major streets are more hazardous than minor streets (Reynolds et al. 2009), especially with parked cars (Teschke et al. 2012). Vandenbulcke et al. (2014) found that complex major intersections increase the risk of cycling accident, because of the dense crossing traffic and many road legs and signs. Harris et al. (2013) found that two major streets intersecting have much higher crash rates, while local streets (with traffic diverters) were safest. Similarly, Kondo et al. (2018) found that cycle lanes are most effective in risk reduction on high volume streets. For all accidents, Marshall and Garrick (2011) found that street network characteristics correlate with safety outcomes for all levels of crash severity: increased street connectivity and number of lanes increase the number of crashes. Streets with 30 km/h speed limit had a reduced risk of accident (Harris et al. 2013; Mulvaney et al. 2015), while higher speed limits are related to increased injury severity (Kaplan et al. 2014).

While complex intersections themselves are associated with decreased safety, denser intersection network is safer for cyclists, especially on fatal accidents, probably because frequent intersections reduce motor vehicle speeds (Marshall and Garrick 2011). The basis for network scale safety planning principles include avoiding conflicts with intersecting traffic and segregating vehicle types (CROW 2016, p. 67). The appropriate measures for street classes are described below. Chataway et al. (2014) suggest that Copenhagen-style segregated cyclist network connectivity reduces fear of traffic, encourages perceived safety and the volume of cycling. To have desired effect, the used separation needs to be coherent and consistent throughout the road sections (FTIA 2014a, p. 42). In a solution where otherwise motor traffic conditions would not require separation for cyclists, a separation might be needed to provide the network function for the cycle path (CROW 2016, p. 102).

Traffic speeds and volumes can be controlled by for instance lowering speed limits, removing some motor vehicle connections or transforming streets into one-way streets (City of Helsinki 2016). Schepers et al. (2017b) argue that removing through traffic from motor vehicles on large calmed areas has been important for cyclist safety increase in the Netherlands.

Separation should be done in tunnels and over bridges over 100 meters long (FTIA 2014a), as bridges along with complex intersections and tram tracks carry the highest risk for cyclist accidents (Vandenbulcke et al. 2014). Harris et al. (2013) also found tram and train tracks to increase cyclist injury risk. However, urban transit can have a calming effect on motor vehicles. Morrison et al. (2019) found cycle lanes (without separation) to prove safe only along tram stops and bus routes, where cycle tracks were also as effective. CROW (2016, p. 124) recommends cycle tracks to be separated from trams on the main cycle network. If cycle lanes along tram tracks are designed, attention need to be put into the design, namely aligning cycle lanes in a large enough angle to avoid tires getting stuck on the tram rails.

Three-level separation is the highest level of service solution and it is recommended on busy streets where the traffic volumes require a separate infrastructure for cyclists (City of Helsinki 2016). Cycle lanes are recommended on relatively calm urban streets with few intersections and shops (Cycling Embassy of Denmark 2012, pp. 77). Mixed traffic is recommended on local routes with low speed limit (30 or 40 km/h) and low traffic volumes (up to 2000 to 5000 vehicles per day). Cycle tracks are recommended on street sections with either 6000 to 7000 vehicles per day or a 60 km/h speed limit. Everything that falls in between these extremes are recommended to be designed as either mixed
traffic, cycle lane or cycle track, or in some cases bicycle street. The recommendations are detailed in (FTIA 2014a, p. 48; City of Helsinki 2016, p. 15; Cycling Embassy of Denmark 2012, p. 53; CROW 2016, p. 102).

The maximum level of separation is always planning cycle paths elsewhere than motor vehicles. In addition to being pleasant for cyclists, increasing the distance between cars and cyclists can reduce the amount of exhaustion fumes produced by combustion engines ending up in the cyclists’ lungs and circulatory systems. The problem is especially with ultrafine particles that spread over distances up to ten meters. In fact, while cycling, air pollution has multiple times greater negative effect on life expectancy than accidents on roads, which both are overcompensated by the positive health effects of cycling. (CROW 2016, p. 35; de Hartog et al. 2010). The avoidance of exhaustion fumes can be achieved mostly in the network and land use scale when designing the route location, and especially in the case of new residential areas that are being planned. Then the separated solution will not be unidirectional. Though, the effect of the fumes is small on local streets with less motor vehicle traffic.

Considerations of separation and deflection related to street qualities are addressed on the chapters about road section and intersection design. To conclude, though separation often increases safety, for network reasons the chosen solution should be a planned with the following features in mind:

- Relevant land use
- Cycle path function
- Street function
- Traffic volumes (cyclists and motor vehicles)
- Number of lanes
- Speed limit
3 Methodology

The methodology of this thesis is threefold (Figure 10). Firstly, the existing cycling safety was assessed with relevance to unidirectional cycling. The traffic accident statistics from 10 years, including manual research of detailed police report descriptions, were analyzed. Secondly, a conflict analysis was done on two relevant study locations with current bidirectional design to find intersection design considerations that do not appear on the accident data. Finally, a seminar workshop input was evaluated in terms of the other findings. Due to the varying nature of the different approaches, the accident data analysis is the primary methodology that the others support. The conflict analyses offer an alternate view upon the design of two chosen study intersections. The workshop produced professional takes on the use of unidirectional design in Espoo, which were reviewed in their relation to the literature findings.

![Figure 10 The threefold methodology used in this thesis](image)

3.1 Accident data analysis

An accident data analysis was conducted to shine a light on the nature of cycling safety in Espoo. The safety was evaluated in terms of unidirectional cycling potential: where could unidirectional infrastructural changes improve safety according to the arguments presented in chapter 2.4. Accident statistics were classified based on street class, minor/major street, intersection type, accident type and right of way. Accidents are differentiated by the severity: death, injury or material damage.

3.1.1 Data validation

Dataset 1: Police reports

The first dataset is the official police reports of accidents occurred in Espoo during 2009-2018, of which at least one participant was a cyclist. The accident classes are classified in terms of the most vulnerable participant. Therefore, the dataset includes both “cyclist accidents (accident class 8)” and those from the “pedestrian accidents (accident class 9)” that included cyclists. The dataset includes 192 cycling accidents and 21 pedestrian accidents (that involve cyclists or mopeds), totaling to 213 accidents. Further classification of the data:

- Location (address)
- Month (1-12)
- Time of the day
Dead (0-1)
Injured (0-3)
Accident type (00-99, appendix 1)
Participants (0-3)
Speed limit (30-50 km/h)
Road construction (Y/N)
Road pavement type
Road surface (bare, dry/bare, wet)
Temperature (0-28 degrees celsius)
Lightness (daylight/ twil ight/dark/streetlights)
Weather (rainy, cloudy but dy, bright)
Traffic lights (none/operational)
Intersection type (uncontrolled/yield sign/STOP sign/signalized/road section/roundabout/other intersection)
Age
Gender (M/F)
Driving license (Y/N)

These data include only the official police statistics and none of possible medical data that is not reported to the police. In the official police statistics approximately 30% of road traffic accidents that lead to bodily injuries are covered, and 100% of fatal accidents (Destia 2019). The issues related to the coverage and underrepresentation of the statistics is discussed further in chapter 5.3. Emergency service data (PRONTO) that is updated monthly was considered and deemed unnecessary since it includes no categorization of accident type, speed limit, intersection type, or other factors relevant to the purposes of this thesis.

Dataset 2: Police reports, detailed descriptions

The second dataset included detailed descriptions of police reports of all traffic accidents reported to the police in Espoo during 2009-2018. The reports were in raw text format and totaled to more than a million rows of text. The non-uniform descriptions included detailed information, such as approaching directions, unfulfilled turning intentions and which participant was suspected of violating the traffic rules. However, the final verdict is unknown. Those accident descriptions with IDs from dataset 1 (that presumably were related to cyclists) were selected out. Dataset 1 was refined with the detailed descriptions from dataset 2, the same 213 cycling related accidents.

During the analysis, 1 cyclist accident and 16 of the pedestrian accidents included no cyclists but mopeds and were removed. “Moped accidents” is a separate mode category (class 7). The data validation resulted in 196 accidents total.

3.1.2 Accident locations

The accident data from datasets 1 and 2 were classified with the current street classes from Espoo, leaving out cyclist-pedestrian accidents (191 accidents). Also single-bicycle accidents (3 pcs) were removed from this classification, resulting in 188 cases. There were four cases where the street classes were not certain. An overview map of the majority of cycling accidents in Espoo is shown on Figure 11. Red dot indicates death, blue
injury and yellow material damage (occurrences: at least 5 material damage or 1 injury and 4 material damage). The accidents are depicted on the most severe manner: red dots can include injuries and material damage, and blue dots can include material damage. Closeup maps of five city centers are depicted in appendix 2.

![Map](image)

**Figure 11** Cycling accidents are not distributed only on the city centers, although the clusters can be recognized (Destia 2019).

**Classification by functional street class**

Street classes represent the functionality of the street on the transport network, and they have common characteristics related to the design and construction, as discussed in chapter 2.1. The streets from the accident data of Espoo were classified in order to detail this relationship in the accident pattern: which type of streets are more commonly associated with accidents, and which of those are related to unidirectional cycling infrastructure. The street type is marked according to the one the participant (cyclist or motor vehicle) was approaching from. In this classification mopeds are considered as motor vehicles while travelling on the carriageway. The street classes in Espoo are presented on Figure 12. The street classification and right of ways were used to differentiate between major street and side street that are expected to have differing qualities when it comes to safety. They were marked for each road user (according to the street they were approaching from). The street classes are:

- Ring road
- Main street
- Regional collector
- Local collector
- Local street
- Solitary cycle path
Classification by intersection type

For the purposes of this thesis travel paths and conflict points that do not include cyclists are ignored. Accidents that include a cyclist crossing the street on a pedestrian crossing or a cyclist track extension are classified to have occurred on road sections. Those cycle paths crossing streets in the proximity of an intersection, however, were classified as intersections, as they are a part of it. Intersection type classification is also included in the official accident statistics. However, the data was inspected, and errors were corrected. Additionally, the data was upgraded by adding “property (lot)” as a new intersection type. Property is usually along a road section but when in proximity of intersections, like cycle paths, they were classified to “intersection”. The nature of the property also varies. Some
large parking lot entrances are unrecognizable from street intersections, and they can have signage or signal control. Such cases were marked based on the intersection type: “yield sign” takes precedence over “property”. Intersections include cyclist-cyclist intersections on solitary paths, but they are dropped on the classification by street area (below). The intersection types are categorized in the following order:

- Signal-controlled
- Roundabout
- Yield sign (give-way)
- STOP sign
- Uncontrolled
- Property (lot)
- Other intersection
- Road section

3.1.3 Reclassification of the accident types

The validated dataset 1 (police reports) included all 191 reported cycling accidents along with 5 cyclist-pedestrian accidents in Espoo (2009-2018). The purpose of the reclassification was to detail out and gather the accidents including cyclists travelling to a direction that is either unexpected for motorists or by other ways increases the chance for accident and could possibly be solved with unidirectional cycling design.

The division for unidirectional cycling potential was done after the reclassification, with the new classes. Since dataset 1 lacks some attributes required for the purposes of this thesis, it was refined with dataset 2: detailed police reports. Firstly, the accident data was revisited according to the official classification. Secondly, the data was reclassified into more detailed accident types. The precise travelling directions, locations on the street and right of ways were marked on the new classes. Currently none of the types 41, 42 or 55 include them. Furthermore, there are no accident types for turning cyclists that were initially travelling along parallel axes (same or opposite direction) to the other road users.

Accident types that are not exclusively for cyclists or pedestrians (00-14, 19-33, 36-40, 50-54, 59, 80-99) are applicable as they are, while types 41 and 42 require a closer examination. Types 41 and 42 include a cyclist on cyclist track crossing motor vehicle travel path. Type 41 includes accidents at intersections, whereas 42 on road sections (cycle track extensions crossing streets). When the cyclist had stopped and remained still for some seconds before starting to cross, the initial travelling direction was discarded as irrelevant (and classified as 41 or 42: crossing directions).

Current cyclist-specific accident types without need for modification

The applicable official cycling accident types (15, 16, 34 and 35) are unambiguous as the motor vehicle is turning on the cyclist who is crossing a cycle track extension (Table 4). These had no need for modification, as the travel directions are known. Types 15 and 16 include a cyclist on cycle path, travelling to the same direction as the other vehicle that is turning. Types 16 and 34 are apparently relevant for unidirectional cycling considerations with cyclists on the left side of the street. Type 55 includes cyclists who are turning in front of motor vehicles while travelling on the cycle path: joining the carriageway. A cycling accident could be classified in any of the other accident types while travelling on the carriageway (or on solitary cycle paths).
Table 4 The current cyclist-specific accident types from official accident type classification (appendix I). Types 41 and 42 were classified further in this thesis, while the others remained.

<table>
<thead>
<tr>
<th>Accident type</th>
<th>Direction</th>
<th>Cyclist side of street</th>
<th>Cyclist default right of way</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Same</td>
<td>Right</td>
<td>Yes</td>
<td>Cyclist on cycle path, other vehicle turned right</td>
</tr>
<tr>
<td>16</td>
<td>Same</td>
<td>Left</td>
<td>Yes</td>
<td>Cyclist on cycle path, other vehicle turned left</td>
</tr>
<tr>
<td>34</td>
<td>Opposite</td>
<td>Left</td>
<td>Yes</td>
<td>Cyclist on cycle path, opposite vehicle turned right</td>
</tr>
<tr>
<td>35</td>
<td>Opposite</td>
<td>Right</td>
<td>Yes</td>
<td>Cyclist on cycle path, opposite vehicle turned left</td>
</tr>
<tr>
<td>41</td>
<td>Varies</td>
<td>Varies</td>
<td>Varies</td>
<td>Cyclist on cycle path, in intersection</td>
</tr>
<tr>
<td>42</td>
<td>Varies</td>
<td>Varies</td>
<td>No</td>
<td>Cyclist on cycle path, elsewhere</td>
</tr>
<tr>
<td>55</td>
<td>Varies</td>
<td>Varies</td>
<td>Varies</td>
<td>Cyclist on cycle path turning in front of or on the side of the other vehicle</td>
</tr>
</tbody>
</table>

Modified unofficial classification of accident types

For the purposes of this thesis, the modified classification includes the travelling directions, positions on the street area and right of ways. Valtonen (2017) proposed unofficial accident types based on the right of way. This thesis has furthered the classification by adding the cycling directions and a distinction on which direction the cyclist was travelling when approaching the accident location. Table 5 describes how the modified accident types were formed (Figure 13). The types are further classified with the letters included on the table. Near/far side of intersection is marked in point of view of the motorist (that is always travelling through the intersection on carriageway). For example, type 41avVE means crossing travel directions (41), cyclist right of way (av), cyclist on left side of their carriageway (V, coming from the right), accident occurred on the near side of the intersection (E).
Accidents with cyclist’s initial path being either same or opposing to the motorist’s (marked under type 41 and 42) were divided to new types 17, 18, 37 and 38. The new types are analogous to their anterior numbers (17 to 15, 18 to 16, 37 to 34 and 38 to 35) where the difference is that the turning road user is the cyclist and not the motorist. In the new classification cycle paths that were initially crossing the motorist’s remained on the classes 41 and 42 and were divided into subclasses based on right of way and travel directions. The cases with road sections where the cyclist’s initial travelling direction is unknown were assigned under 42 (perpendicular crossing).
Figure 13 New unofficial accident types proposed for the purposes of this thesis. The yield sign symbolizes right of way, while these types are used also on uncontrolled intersections and crossings.

Limitations of the new modified classification

Setting up a classification to depict the physical world with decades of design is bound to have some arbitrariness. The difference between type 41 and 42 can be marginal, depending on how far along an area is defined to be included in the intersection. Cyclist crossing
cycle track extension near an intersection could be differentiated for or classified as 42
since none of the conflict did not relate to the crossing street. However, areas next to
intersections are defined as intersections (though the distinction is shady) and noting the
intersection is relevant since the driver has different stance on making decisions when
there is known to be crossing traffic. Similarly to the distinction of intersection and soli-
tary cycle path, the difference between crossing travel directions and turning (type 41 or
42 and 15, 16, 17, 18, 34, 35, 37 or 38) can be slight. Depending on the intersection design
and driving speeds it is impossible to unambiguously define the difference when the ve-
hicle is turning and when it has made the turn and assumed a straight path.

Taking into account situations where both the motor vehicle and cyclist were turning be-
fore crossing would double the number of new accident classes. Therefore, motorist turn-
ing types (15, 16, 34 and 35) are not distinguished by the cyclists’ turning movements,
and neither do the new cyclist turning types (17, 18, 37 or 38) take into account the mo-
torist’s possible turns.

In reality, right of way is situational. For example, when a cyclist going the same direction
as the car on side street, but turning in front of it to cross, the yield sign dictates cyclist
right of way. Technically the cyclist travelling to the same direction will start to travel to
the perpendicular direction at the moment of turning towards the crossing, but in a case
such as this the right of way depends on the situation. If the cyclist turns suddenly, with
high speed and does not signal his or her turning, the driver cannot be expected to know
the cyclist would cross paths. On the other hand, the driver should approach the intersec-
tion with a speed that the vehicle can be stopped. The detailed police reports include only
a suspect and no final verdict. This thesis will not pursue assessing blame but assigns
right of way on theoretical grounds of specific travelling directions without any of the
individual case variables (e.g. speed and signaling).

Right of way can be achieved by position on uncontrolled intersection, yield sign (or
signal-control). The classification does not specify on whether an intersection is three or
four-legged. This could be useful, since three-legged intersections have less conflict
points and are safer by default. Then again, the number of cyclist crossings could also be
noted, as it increases the complexity of the intersection. The announced direction the turn
was about to be made was noted in the statistics, leaving the fourth leg of the intersection
somewhat irrelevant. Though, very often the direction of potential turn was not reported.

The theoretical right of way of the proposed classification can be misleading and hide
behavior of the actual events. It is possible that the specific right of ways of individual
cases differ from the theoretical ones. For instance, an accident type might prove to be
most common when cyclists are in fact not obeying the right of ways set by the legislation.
Noting the individual case differences could be a topic for another study, though the in-
formation is often missing from the detailed descriptions and it is based upon the story of
one or more participant’s memory of the incident or the police officers’ suspicion of how
the event rolled out (that is largely based upon the participants or witnesses).

3.1.4 Identifying potential accident types

Given the safety decreasing nature of BCPs at intersections, the objective of the safety
analysis lead to identifying those accident types that could be deemed as potential for
unidirectional cycle paths to solve as a countermeasure. Additionally, accidents involving
a turning motor vehicle (but cyclist not on the left side of the street) were separated as
their own classes, as on the design covered in chapter 2.5 could be used also to countermeasure these. These accidents were also compared with the street hierarchies, as minor and major street have different functionalities and should be addressed with different measures.

Classification by location on the street area

The street area location classification was used to determine where exactly the cyclist was travelling when the accident occurred. While the relevant types for this thesis are almost exclusively intersections, properties can also be relevant, as they are in some cases equivalent of intersections (even without intersection in proximity). Cycle path crossings on road sections, on the other hand, are not relevant, as by default they would be needed also on a unidirectional system. When in close proximity, solitary cycle paths joining at intersections were considered as an extensions of the cycle paths adjacent to the streets.

Some of the classes overlap. For instance, a cyclist can be travelling on solitary cycle path that is on road section. To retain the relevant information the classes were laid out in the following order, cyclist position on:
- Cycle path (no crossing between modes)
- Carriageway
- Left side of the street
- Motor vehicle turning over cyclist (that is on the right side of the street)
- Right side of the street (crossing intersection)
- Road section (cycle path/street crossing)
- Unknown side of the street
- Other place (mainly parking lot)
- Unknown place

Accidents occurring on road sections can be relevant to unidirectional design if they include cyclists on the left side of the street or cars turning over them, basically when entering or exiting properties. However, most cyclist street crossings on road sections do not have relevance since they would by default occur on a unidirectional path as well (whether more or less so is arguable and affected by the network design that affects street crossings, as discussed chapters 2.4.). The new accident types were grouped in the following way.

Class 1: Cyclist travelling on the left side of the street

As discussed in chapter 2.4., the literature suggests that BCPs increase accident risk by providing cyclists with a travel direction that differs from motor vehicles: cyclists travelling on the left side of the street. The extreme case of unexpected travel is when the driver is about to turn right and therefore especially has fixed his or her attention towards vehicles approaching from the left. The unfulfilled turning intentions of the motorists were marked but not classified as distinct types. Usually the problem of left-sided travel is defined with only crossing travel directions. However, here all the cyclists on the left side are included (also when turnings occurred). The accident types involving cyclists travelling on the left side of the street are: 16, 34, 17avE, 17pvE, 41avVE, 41pvVE, 41avVJ and 41pvVJ (Figure 13).
Class 2: Motorist turning over cyclist (on the right side of the street) 

Turning accidents can be countermeasured with certain intersection design that is applicable for unidirectional paths. Some of the countermeasures (deflection, raised crossing) are applicable also for BCPs, which makes this class not inherently about unidirectional design, but more of an additional point of interest. In accident types 16 and 34 motor vehicles are turning over cyclists but included in the primary class 1, leaving class 2 with accident types: 15 and 35. Additionally, all turning accidents were considered as a group and left and right turns individually, as the qualities of the turning accidents do not limit to the side of the street.

Those accidents that did not fall within either classification were compared either as “rest” or to those at the intersection area (and not potential). Accidents categorized further in classes 1 and 2 were mapped out in proportion of all and in relevance to street class, major/minor street, intersection type, place on the street area and right of way to find out in which traffic environments the potential exists. Additionally, the unfulfilled turning intentions of the drivers were studied. Reference data from other Finnish cities were classified in these terms to offer a comparison for the data from Espoo. The results are presented in chapter 4.1.

3.2 Traffic conflict analysis

3.2.1 The conflict method

Traffic accidents are rare events. Traditional methods for traffic safety analysis (accident data analyses) have shortcomings which make it difficult to learn the whole nature of traffic safety. The issues with traditional methods include:

- The reactive nature of the analysis
- Small data quantities
- Limited quality of data
- Data is reconstituted after and with a bias towards more damaging events
- Lack of information on the behavior before impact
- Difficulty to attribute collisions to a cause (instead of responsibility) (Saunier 2014; Essa and Sayed 2018).

Conflict analysis is a different approach to evaluating safety of a traffic environment and it may yield results that are undetectable in a conventional accident-based analysis. A relationship exists between traffic conflicts and accidents (Laureshyn 2010; El-Basyouny and Sayed 2013). Such relationship is illustrated with the safety pyramid on Figure 14.

![Figure 14 Illustration of traffic events (Laureshyn and Várhelyi 2018, originally Hydén 1987).](image)
The theoretical behavior of road users on has been modelled for traffic flow purposes. On an unsignalized intersection the driver has no cue on when to make their move in intersecting the traffic stream. According to the gap acceptance theory, there is a gap in an intersecting flow that a driver is willing to accept when entering an intersection, which is defined as the critical gap. The gaps are measured in time and they are equal to headways. (Troutbeck and Brilon 1997). Gap acceptance is usually considered at intersections with major/minor streets crossing (Dutta and Ahmed 2017). Gap acceptance theory can be used to explain the behavior of road users when conflicts occur. The gap indicates the place or time interval the driver decides to merge onto or cross the conflicting flow (Figure 15). When the volumes are high, drivers will need to accept gaps that might not be adequate. When a conflict occurs, the gap has evidently been insufficient.

![Figure 15 Schematic diagram of gap (Dutta and Ahmed 2017).](image)

The definition of a conflict varies. In the classic definition conflict is: “an observable situation in which two or more road users approach each other in space and time to such an extent that a collision if their movements remain unchanged” (Amundsen and Hydén 1977, cited by Laureshyn and Várhelyi 2018). What constitutes as a conflict is determined with objective conflict indicator values along with subjective evaluation of the situation.

The early information on specific conflict methods is mostly about motor vehicle and highway traffic. Less attention of conflict analyses in the past have been on cyclists or pedestrians which are the more vulnerable road users (Van Hamperen et al. 2017; Kraay et al. 2013). A motivation for choosing conflict analysis as a methodology for this thesis was to fulfill some of the shortcomings that may exist with working solely with accident data by taking another way of looking at two specific intersections. Especially in Espoo, cycling accidents are rare, which is in part because of the low reporting rate. Traffic conflict techniques as direct observation of traffic events is one solution to tackle the problem of underrepresentation of cycling accidents in police reports (Wegman et al. 2012). Ideally, traffic conflict data is used not to replace but to compliment conventional safety analysis (Laureshyn and Várhelyi 2018).

Since there exists less conflict theory for bicycle-specific traffic, the general methods are applied to urban cyclist situations. On urban areas, the speeds are bound to be lower than on highways and similar conflicts by default have larger severity because of the vulnerability of cyclists. According to Silla (2016, p. 43) the interaction with pedestrians and cyclists between cars is especially interesting research target for the conflict method is, since cyclist accidents have not decreased as quickly as car accidents have in recent years in Finland.
There are different ways of performing a conflict analysis. Some measure different key figures with varying manners and complexity. The threshold values for conflict indicators vary. The common threshold values are 1, 1.5 or 2 seconds, and events with larger values should be discarded (Kraay et al. 2013; Hayward 1972; Shelby 2011). Some studies have used larger values, such as Zangenehpour et al. (2016). Different countries have their own traffic conflict techniques, and the ones referred to in this thesis are the Swedish Traffic Conflict Technique (Laureshyn and Várhelyi 2018) and the Dutch DOCTOR method (Kraay et al. 2013). There has been development in uniting the techniques in order to get more comparable results between different countries (Kraay et al. 2013).

In this thesis, the approach of the conflict analysis is to use video footage to record apparent conflicts, determine key figures that verify that they in fact constitute conflicts, and map out them so that they yield information of the characteristics of the study locations. The characteristics can then to some extent be used underline intersection treatment qualities related to unidirectional cycle path design. The methodology used in this thesis is a simplification of the Swedish technique in conflict identification. Different types of conflicts yield different results and can be detected with different indicators. Common conflict indicators that are derived from a conflict analysis are Time-To-Collision (TTC), Post-Encroachment Time (PET) and speed. These indicators are used in this thesis to determine which of the traffic events observed constitute as conflicts. They are described on below on “Conflict identification”.

### 3.2.2 Determining the study locations

The locations with accident history might have potential for conflict analysis. Working out to identify potential intersections started with gathering attribute data from occurred accidents from the past ten years. This data was gathered from Destia’s iLiitu service (2019), described with detail in chapter 3.1.1. As cycling accidents in Espoo are rare, they do not cluster much into any specific intersections.

**Elimination of locations**

The 196 cycling accidents from dataset 1 formed the initial group for finding study locations. The accident sites were manually sorted through by determining whether they could have need for unidirectional cycling and an application for a conflict analysis. The elimination process is described below:

- Pedestrian accidents
- Outside of the study area
  - The proximity of the Coastal Railway is the study area chosen for this methodology. It is in a stage of development that has the most application for unidirectional cycling design
- Outside of the unidirectional cycling network grid sketch
  - The grid sketch was background information from the city of Espoo
- Road sections
  - The conflict analysis is done at intersections where there are conflict points. Though, this thesis includes considerations about unidirectional design on road sections.
- Signal-controlled intersections
  - Signal-controlled intersections are not the study target of this thesis and have less to offer for a conflict analysis of this scale.
Roundabouts
- The accident data included few roundabouts as was expected since they are a rarer solution and are not the focus of this thesis. Roundabouts offer a smaller number of conflict points.

Solitary cycle paths (without adjacent street)
- They have little to offer for unidirectional cycling considerations or conflict analyses.

The elimination reduced the number of potential sites from 191 to 11. A site visit on the 11 locations included a general observation of traffic, street geometry, possibility for unidirectional design and, most importantly, the grounds for a conflict analysis. This elimination removed three sites as unacceptable. Lansapuontie and Kilpitie had a stop sign inserted after the accident, thus reducing greatly potential conflicts. Espoontie and Kirkkojärventie had construction and a pedestrian and cyclist track temporarily removed, thus it would not yield proper results. Sunantie and Kirstintie was also removed as too difficult to film properly. In theory any location can be filmed. The question is which kind of angle can the camera be placed on. When using a portable camera tower that is mounted on a vehicle, it requires certain space on the street area with relatively even ground. Using a lower tower (or none at all) produces video with worse perspective, more blind spots and a risk of blinding with increased sky exposure. The video capture details are discussed further below. This resulted with potential eight locations.

The remaining eight locations were all adequate for a study and were different in multiple ways that cannot be compared without subjective judgement. These were different traffic environments with different road functions. Some of the sites had more suitable places to mount a traffic camera without creating a distraction that meddles with traffic behavior. Some had higher traffic volumes, as others had worse visibilities or road markings. City of Espoo (2019b) has conducted cyclist volume calculations, but since none of them are directly measured from these study locations, they are of little use. In the absence of cycling data, the route importance was evaluated by reasoning origins and destinations, and whether the connection was major or secondary. The qualities of the intersections are compared in appendix 3.

Tuomarilantie and Tuomarilankatu intersection was selected for a case study. The street geometry of the major street is wide, which might cause motorists to exceed the speed limit (50 km/h). It is also planned to be a possible unidirectional connection, which requires further considerations on the intersection design regarding continuity. It is an especially interesting location for the conflict analysis, as there occurred overall eight accidents in 2009-2018, of which five included cyclists. Kirkkokatu and Kaivomestarinnitity was selected as another study site. It is an interesting site with high traffic volumes, attractions and shared cyclist and pedestrian paths on both sides of the street. Kirkkokatu is one of the two routes connecting to Espoon Keskus from the northern side, and it has had a high increase in cycling volumes.

Choosing of the locations was affected by the reality of the current traffic environments. There might exist locations at such stage of development that unidirectional cycling could be easily implemented there, and there the function would make more sense. However, it is common that these locations have low traffic volumes and are thus not valid for a conflict analysis.
3.2.3 Execution of the video recordings

Traditionally conflict analyses have been done with on-site observations and speed estimations. There are advantages in using a video recording instead of an on-site observation (Essa and Sayed 2018). Firstly, video recordings can be re-watched multiple times and the analyzing process can be assisted with automation. Secondly, video footage combined with timer and distance measurements is a more accurate and objective method, thus less dependent on the qualities of the observer. According to Kraay et al. (2013), a functional speed evaluator estimates the speeds with maximum of 20% mistake. It is also arguable that a video recording, if implemented well, draws less of the unwanted attention of road users. Video recordings provide all in all a better documentation and transparency as they can be reviewed afterwards. The shortcomings that need to be attended about the video method include a limited area of view and perspective and lens distortion. It is also possible that the video method might lack a certain holistic approach that an on-site observer can produce (Laureshyn 2010).

Models of the intersections were developed to get the distances for conflict identification (appendix 4). The distances were measured between the blue lines equipped with numbers. Green lines indicate assumed travel paths for motorized vehicles and red ones for cyclists (and pedestrians). This model is a simplification, like all models by definition. There is an infinite number of precise paths a road user can take, as there is an infinite number of locations in which the conflict may occur, between the fixed (blue) lines. Here the cyclist (red) travel paths are not differentiated by the directions which is a further simplification. In reality, cyclists are prone to taking the right side of the path while remaining between possible pedestrians and the motorized traffic.

The videos were recorded week apart, during the week: Tuesday 10.9. (Tuomarilantie and Tuomarilankatu) and Tuesday 17.9.2019 (Kirkkokatu and Kaivomestarinniitty). A camera mast was used (Figures 16 and 17). The chosen days were with low chance for rain. While sunlight can increase the number of cyclists, it also creates polarization of the video footage which makes it harder to interpret. A compromise was made concerning the weather: the first study day was sunny and the second cloudy but not rainy.

![Figure 16 The camera equipment used in the video analysis.](image)
On both study locations the camera mast was aimed to be positioned to:

- Have recognizable range to all points of interest
- Cover the maximum amount of the intersection area
- Have correct perspective to ease movement detection for all directions
- Minimize the sky and sun exposure (risk of blinding)
- Avoid drawing the attention of road users
- Have level terrain for the camera mast

The process included inescapable measurement errors:

- Simplification of the travel paths
- Locations not strictly on the spot but in proximity
  - With some events the braking lights of the car helped recognize the exact moment the breaking started.
- 5 cm from distance measurement wheel
- 1/30 s video lag
- Perspective error at position evaluation
- Lens distortion error
  - Minimized by well-placed static lines
- Car body length differences
  - An average length of 4 meters for a car body was used to help determine the braking distances

![Figure 17 Tuomarilantie site. The camera mast is located on the far side of the intersection. One of the white markings, which were used to evaluate distances, is visible on the pavement.](image)

### 3.2.4 Conflict identification

The processing of the video footage (Figure 18) yielded data of possible conflict situations that were studied further in order to produce conflict indicators. The conflict indicators (described below) were used to determine which of the situations constituted as conflicts, and to evaluate their severity. None of the possible motor vehicle-motor vehicle or motor vehicle-pedestrian conflicts were noted since they are not the focus of this thesis. As a side note, no accidents happened during the time of the video recordings. Every
vehicle crossed conflict points between some route but not necessarily at the same time. The travel directions were not taken into account when counting the volumes. Cyclists that cycled at least a part of the trip were noted as cyclists. Mopeds on the carriageway were considered as any motor vehicles, while the few mopeds driving on the cycle path were discarded from the volume calculations (and resulted in no conflicts).

![Screen capture of the video footage (Kaivomestarinniitty)](image)

**Figure 18** Screen capture of the video footage (Kaivomestarinniitty) with added static lines for distance evaluation.

**TTC and Time-To-Accident (TA)**

Time-To-Collision (TTC) is a continuous model of vehicles on a collision course introduced by Hayward (1972), who deems TTC as crucial for defining a conflict (although he used the term “near-miss”). The simple definition for TTC is the time to collision if vehicles that are on a collision path would continue without adjusting theirs speeds (Kraay et al. 2013). A model of vehicles’ collision courses is presented on Figure 19.

![Time-To-Collision](image)

**Figure 19** Time-To-Collision for perpendicular and parallel travel paths (Laureshyn et al. 2010).

Time-to-Accident (TA) is the value of TTC retrieved at the critical moment an evasive action is taken. TA is used in the Swedish conflict technique. Minimum of TTC and Time-to-Accident (TA) are similar indicators, but TA does not require the whole curve of TTC to be generated, but instead used the TTC value at one point in time. TA can also be applied to events that result in a collision. (Laureshyn et al. 2010). Results from Van
Hamperen et al. (2017) found a high correlation between TA and TTC\textsubscript{min}. For the purposes of this thesis, the TTC conflict indicator used is TA. In reality, the collision courses are seldom perpendicular. However, in order to calculate any numbers, simplifications need to be made. When the vehicles’ trajectories are presumed to be perpendicular, TA values were calculated using the following formula from Laureshyn et al. (2010, modified):

\[
\begin{align*}
\text{TTC} &= \frac{d_2}{v_2}, \quad \text{if} \quad \frac{d_1}{v_1} < \frac{d_2}{v_2} \\
\text{TTC} &= \frac{d_1}{v_1}, \quad \text{if} \quad \frac{d_2}{v_2} < \frac{d_1}{v_1}
\end{align*}
\]

TA is calculated at the time evasive action begins. The value of TA is the time it would have taken for the road user to collide, if no action were taken. If a collision is possible on several combinations the higher TA value is the one which indicates the conflict, as is depicted in the formula. In other words, if either road user takes an evasive action large enough, the collision is avoided. The formula from Laureshyn et al. (2010) includes an additional term for verifying the collision course. As a simplification of the method, the collision courses were instead estimated as “planned trajectories” by repeated evaluation from the video footage. Only average speeds can be determined with proper accuracy. At some point it can be detected that the road user starts to slow down but as the point is inevitably somewhere between the measured lines. A TA threshold of 2 seconds was chosen for events to constitute as conflicts, and larger values were discarded.

**Post-Encroachment Time (PET)**

Post-Encroachment Time (PET) is a conflict indicator that describes the time between the first road user leaving and the second road user entering the shared area on their collision paths (Figure 20) (Laureshyn et al. 2010). PET value is the time difference between these vehicles ($t_2 - t_1$). With car on car conflicts, PET might be difficult to obtain since the collision paths are often not perpendicular. There are more complex models on calculating conflict indicators with angled vehicles. However, since the area a bike has is small, almost one-dimensional, both PET and TA become easier to obtain. Usually, when the conflict involves stopping of at least one of the vehicles, PET indicates no conflict, since it takes long for the stopped vehicle speed up and reach the area the other vehicle occupied. Therefore, in these cases TA was the relevant indicator. Same as with TA, a threshold of 2 seconds was chosen for PET to constitute a conflict.

![Figure 20 Post-Encroachment Time (PET). (Allen et al. 1977, cited by Laureshyn et al. 2010).](image-url)
**Speed**

The speeds of road users leading to conflicts give additional information, mainly on the severity of the conflicts. As Laureshyn and Várhelyi (2018) describe, the TTCs of two different incidents can be the same but one of them has much higher speeds and is therefore more severe as a conflict. With TA, the speeds of the road users were calculated at the moment right before the start of the evasive action. In the case of PET, the speeds were calculated when approaching the shared area.

Conflict severity is used as a concept in research with different meanings: probability of crash, magnitude of potential damage, or a combination of both of the above (Shelby 2011). TTC values lower than 1 second are usually considered as severe conflicts (Shelby 2011). Though the conflict indicator values refer to the severity, in this thesis, conflict severity is not classified with a quantitative method. Only pre-conflict speeds were measured.

The calculations described above were used to determine which events constituted as conflicts. Those with appropriate TA or PET (less than 2 seconds) were accepted while others discarded. The detected conflicts were compiled on maps that are presented on “Results”. The results include also “before-after” maps of the conflict points of these intersections with a hypothetical unidirectional design. In addition, the descriptive information about the conflicts obtained from the video footage tells more about the road user behavior on conflict situations, mainly respect to right of way (yielding), and provides a context for the indicator values.

### 3.3 Workshop during VeloFinland 2019

VeloFinland is an annual seminar organized by the Cycling Union of Finland (Pyöräliitto 2019) that gathers professionals and activists of cycling planning to discuss current topics concerning cycling in Finland. In 2019 it took place in Espoo and it included a workshop organized by the city of Espoo that was also used as a supporting methodology of this thesis. The workshop was titled “Unidirectional cycle paths in Espoo - Possibilities and challenges”. Given the nature of the seminar, the majority of the participants were professionals in the transportation field. The purpose of the methodology was to include the “voice of the cyclists”, which consists of cycling activists and professional planners.

The workshop provided ideas and sketches from some 45 participants attending. The briefing included a questionnaire whether unidirectional design is applicable for Espoo, and in the end this question was repeated. The participants were assigned into groups with the following tasks.

**Task 1: Route selection**

In the first task the participants were given an area with a distinct origin from Hämeenvaara and a destination in Leppävaara station. The objective was to draw a network level plan that connects the origin and destination, focusing on how to develop the cycling route, which routes to prioritize along the way. The goal was to achieve a fluent, safe cycle path that controls too fast cycling along Leppävaaranraitti, which is a high-volume pedestrian route.
**Task 2: Case Lintuvaaranantie**

The cycling connection along Lintuvaaranantie is presently incoherent and causes frequent crossings. The second task involved sketches of unidirectional cycling paths along the way and the participants were assigned to evaluate the pros and cons of them. The pros and cons effects were to be evaluated concerning: cyclability, accessibility from all directions, safety and effects for different modes, streetscape, greenery and costs.

**Task 3: Where unidirectional solutions could work?**

The third task included planning of the criteria the areas and streets for unidirectional infrastructure could be chosen with. The task included both the general planning on principles and a specific marking of streets and areas on a map.

The assigned tasks give the contexts that the input was coming from. The results of the workshop were evaluated in relation to the literature and other methodology of this thesis. They are described in the next chapter.
4 Results

4.1 Accident data analysis

The results from the accident data analysis include the modified classification that was classified further to attain the potential of unidirectional cycle paths in terms of locations: intersection type, street class and major/minor street travelled. Additionally, turning accidents are noted, as they might be countermeasured with the design described in chapter 2.5.

4.1.1 Official accident type classification revisited

The cycling accidents from Espoo during 2009-2018 (dataset 1 refined with dataset 2) were classified according to the official classification into types 0-99 (appendix 1) while fixing errors. The results show that accident type 41 is even more common than was originally thought (Figure 21). Types 41 and 42 together make up for 100 accidents, that is 51% of all cycling accidents. Clearly, these types need to be examined further, as is the purpose of the new classification. The “other accident” types (types 9, 29, 39, 49, 59 and 99) turned out much fewer than what was (and is) initially marked on the statistics, as the detailed descriptions revealed them to belong to actual type classes. Especially type 49 decreased from 17 cases (9%) to 2 cases (1%), as it was reserved only for the truly misfit cases (such as a suspected manslaughter attempt). Type 15 was overrepresented as a result of a systematic error where motor vehicles arriving at a three-leg intersection crashed on the near side and were marked as “turning”. Since the turn had not yet actuated these were assigned mostly on type 41. The same pattern is not present on type 34, which increased considerably as a result of the revisit.

![Figure 21 Official accident type classification, errors are fixed on the revisited version.](image-url)
The revisited accidents are presented on Figure 22. The characteristics discussed further with the more detailed accident types are applicable with the official classification as long as one reduces the more detailed types back to their original types: new types without P in the end to type 41 and with P to type 42, as P signifies “cycle path” (crossing without intersection).

The accidents are heavily located at intersections (Figure 23). The most common intersection types are: “yield sign” (39%), “signal-controlled” (9%), “uncontrolled” (9%), “property” (8%), “other intersection” 5%, “roundabout” (3%) and “stop sign” (2%). Some of the accidents classified to uncontrolled intersections happened on solitary cycle paths either between two cyclists or cyclist and a moped. “Other intersections” include cycle path extensions crossing ring road or highway intersection ramps and those with peculiar design.

25% of cycling accidents occurred on road sections. The class consists of accidents on solitary cycle paths and those adjacent to streets, including crossings (without intersection in proximity). Nearly half (21) of these 49 accidents have cyclist crossing the street on a pedestrian crossing. 12 accidents occurred on cycle path, 5 on carriageway and 4 precise locations remain unknown. This distribution is not controlled by the number of different intersection types in the city.
4.1.2 Modified accident types

The new unofficial detailed accident types and their occurrences are shown in Figure 24. Figure 25 shows all of the accident types (new classification with old applicable types) and their spread to intersection types. The widespread of the types is partially explained by missing data, for which they could not be assigned to their rightful types. The types are classified further in terms of potentiality below.
Figure 24 Reclassified accident types that produced data. The number of accidents of each type are shown on the upper right corner. The empty slots are new types that had zero data points. All of the new types are presented in Figure 13.
4.1.3 Potential accidents for unidirectional design

The accidents that could potentially be eliminated with unidirectional design are presented in Figure 26: class 1 (cyclist on left side of the street) 27% (53 pcs). This is the most common class and it has safety improvement potential with unidirectional design, as described in chapter 2.4. An additional 8% of the accidents had cyclist on unknown side of the street. Class 2: motor vehicle turning over cyclist, on right side of the street, produced 8% of the accidents (16 pcs). Accidents with cycling on the carriageway make up for 8% of all cycling accidents. More than half of these (9 pcs) included a local street.
Few of the accidents lead to death (6 pcs) or only material damage (23 pcs), while a great majority of reported accidents resulted in bodily injuries (167 pcs). The severity distributed very evenly among the accident locations. Although, two deaths occurred while cyclist was travelling on the left side of the street, and three on an unknown place (missing data). “Fatal accident” is defined as a party dying within 30 days of the accident. Injury is defined as including a party seeking or taken into medical attention afterwards, and material damage is defined as only damage reported on either of the vehicles involved. The accident data lacks a more accurate classification on accident severity.

The proportions of cyclists’ locations on the street area on unsignalized intersections are presented on a comparison between other Finnish cities (Figure 27). While left-sided cycling leading to accident is not as common in Espoo (54%) as in the reference cities, it is more common than cyclist coming from the right. Right-sided cyclist accidents make up for the rest (14% motor vehicle turning and 33% going straight). Solitary cycle paths joining three-legged intersections where an adjacent path would have been, were included as adjacent cycle paths. The comparison is not entirely accurate, as there are differences on how the data was classified, and the results vary depending on which intersections were included on the comparison:

- Data from Helsinki 1990-94 and multiple cities (Helsinki, Hämeenlinna, Mikkeli and Ylivieska) does not include road sections where motor vehicle collides with cyclist on cycle path (properties) which the data from Espoo and Helsinki 2007-2016 include.
- Data from Helsinki 2007-2016 and multiple cities include only give-way intersections, while the data from Espoo and Helsinki 1990-94 include all unsignalized intersections.
In Figure 28, the potential of unidirectional design in improving cyclist safety is laid out in terms of street class. The most potential exists on the higher street ranks: regional collectors and main streets, and it does not differ much from overall numbers. Both the overall proportion and potential ones with cyclist on local street are low. The number of cyclist-moped accidents on solitary cycle paths is quite high. The figure shows how scarce cyclist-cyclist and single-cyclist accidents are.
Figure 29 presents the potential by intersection type. The most potential lies on give-way intersections (yield sign) followed by signal-controlled intersections. Road sections (excluding properties) are irrelevant, as road sections will have crossings even with unidirectional design. The two cases are due to peculiar design creating “quasi road sections”. The number of accidents on roundabouts was small: four of the seven accidents had cyclist on the left side. Specific accident types for the potential accidents are shown on appendix 6, as well as overall intersection types by the street rank.

Turning accidents form a large part of cyclist accidents (36 pcs, 18%). Those turning accident where the cyclist is not on the left side (marked with blue) consist mostly of type 15, right turns over cyclist (12 pcs), while type 35, left turn was rare (4 pcs). Of all accidents with motor vehicle turning, the right turn accounted for 26 accidents, while left turns only 10 accidents. These occurred all with both vehicles on major streets, and with collectors or main streets as street classes. Of accidents on signal-controlled intersections, the turning types make up for 78% (14 pcs).

<table>
<thead>
<tr>
<th>Unidirectional design potential by intersection types (196 pcs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No obvious potential</td>
</tr>
<tr>
<td>Unknown potential</td>
</tr>
<tr>
<td>Cyclist on left side of street</td>
</tr>
<tr>
<td>Turning over cyclist (right side of street)</td>
</tr>
</tbody>
</table>

Figure 29 The potential retrieved from accident data of unidirectional design depicted in terms of intersection type. The most potential exists on give-way intersections with yield signs.

The most common situations of the potential accidents had motor vehicle approaching from the side street and those with both on the major street (usually the same streets and turning accidents) (Figure 30). The clearly most common accident type (41avVE) is when the cyclist is crossing the main street and motor vehicle is approaching the intersection (from the side street) and fails to evade the cyclist coming from right. The rightmost bar includes one case of turning over where the intersection was uncontrolled. Otherwise the accidents consist of give-way (yield sign) and signal-controlled intersections.
Potential on near side accidents

If we look at unidirectional potential in the strict sense, accident occurred at near side of the intersection, the cyclist was coming from the right on 29 times (accident types 17avE, 17pvE, 18avE, 38avE, 38pvE 41avVE and 41pvVE). Conversely, the cyclist was coming from the left on 19 times (types 18pvE, 37avE, 37pvE 41avOE and 41pvOE). There the potential is 60% of the accidents. Figure 31 presents a comparison between the potential accidents on the near side of the intersection (excluding accidents that occurred on the far side and with turning).

- Data from Helsinki 2007-2016 and multiple cities include only give-way intersections
- Data from Helsinki 1985-1994 includes all unsignalized intersections
- Data from Espoo 2009-2018 includes all intersections (three are properties and one is signal-controlled)
Figure 31 A comparison of proportions of potential accidents on the near side of the intersection (Pasanen and Räsänen 1999; Räsänen and Summala 1998; Härme 2018).

Figure 32 shows the unfulfilled turning intentions of drivers colliding on the near side of the intersection. On the right are the potential accidents with crossing directions (cyclist travelling on the left side of the street). Those on the far side of the intersection are excluded, as with them the turn is in motion or completed (also turning accidents). The data includes three-legged intersections where some of the turn possibilities were not open. Though the data is scarce because it is not collected regularly, driver about to turn right is the most common with nine accidents, and there was only one accident for left turns.

Figure 32 The unfulfilled turning intentions of road users colliding with cyclists approaching from the left side of the street and near side of the intersection (from the driver’s perspective)


4.2 Conflict analyses

4.2.1 Conflict points

Figures 33-36 show the changes in conflict points a unidirectional design could produce on the specific conflict study sites. As expected, the number of cyclist-motor vehicle conflict points on the unidirectional design is around half of that of a BCP. This conflict point illustration does not account for rear collisions that could occur when travelling on the same direction and one road user is turning. The conflicts between cyclists and pedestrians are not visible on the comparison. It is arguable which conflict points on the cycle path are counted in, since cyclists assuming their side of the path do not cross paths on some turns. Then again, it is common that cyclists (along with pedestrians) use the width of the path liberally, especially when about to cross. Whether to count the turning vehicles as their separate conflict points (not yet merged) or as the same as the vehicles travelling straight is dependent on the intersection design and individual travel paths that can vary. The reduction of the number of conflict points on these sites is shown on Table 6.

<table>
<thead>
<tr>
<th>Site</th>
<th>Kaivomestarinniitty</th>
<th>Tuomarilankatu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclist from the left</td>
<td>From 9 to 4</td>
<td>From 8 to 6</td>
</tr>
<tr>
<td>Cyclist from the right</td>
<td>From 9 to 5</td>
<td>From 8 to 5</td>
</tr>
<tr>
<td>Cyclist-cyclist*</td>
<td>From 14 to 3</td>
<td>From 8 to 3</td>
</tr>
<tr>
<td>Motor vehicle-motor vehicle</td>
<td>None (6)</td>
<td>None (6)</td>
</tr>
</tbody>
</table>

The comparisons are not entirely accurate since the redesign with unidirectional cycle paths has taken up some more space on the street area, including the separation lanes that were used to achieve the width of quality cycling and pedestrian paths. There are different options in the recreation of the cycle paths. For the cycling route on Tuomarilankatu to work as unidirectional, an additional crossing was introduced (Figure 36). Another way would be to keep some paths bidirectional. Even with the additional crossing the conflict points are reduced. Though, the fluency of the major connection is disturbed further with the additional crossing.

Reducing the number of conflict points does not automatically translate to only reduced number of conflicts. The same number of cyclists and motor vehicles will be travelling through, and some of the conflicts are bound to shift to the remaining points. For instance, crossing the street might increase. The comparison will however shed a light on which types of conflicts become obsolete (with the exception of illegal contraflow), and for which there is arguably more driver attention available (discussed further in chapter 5.1).
Figure 33 Current conflict points on Kirkkokatu and Kaivomestarinniitty intersection with BCPs.

Figure 34 Conflict points of hypothetical unidirectional cycle paths on Kirkkokatu and Kaivomestarinniitty intersection.
Figure 35 Current conflict points on Tuomarilantie and Tuomarilankatu intersection with BCPs.

Figure 36 Conflict points on hypothetical unidirectional cycle paths on Tuomarilantie and Tuomarilankatu intersection.
4.2.2 Detected conflicts

In terms of conflict indicator values, there are three types of conflicts. In the clear majority of conflicts, the road users crossed paths in space and time, and one or both decelerated to avoid collision. These were identified by calculating the TA values. Conversely, when neither road user was decelerating, the TTC value did not exist as the vehicles never were on a collision course, no matter how close the pass was. There PET was used as the relevant indicator. When either of the road users stopped, evidently the PET values rose so high that TTC was in turn used as the relevant indicator. There was only one conflict detected where both a visible deceleration and a close post-encroachment occurred, and the combination could be used. Table 7 presents the detected conflicts of both sites. ID number includes the hour of the conflict.

Table 7 Calculated conflicts from both sites. C = motor vehicle, B = bicycle

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>Maneuver type</th>
<th>Location</th>
<th>V_c (km/h)</th>
<th>V_b (km/h)</th>
<th>TA (s)</th>
<th>PET (s)</th>
<th>STOPPED VEH</th>
<th>ROW</th>
<th>YIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuomarilankatu</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14b</td>
<td>C-B</td>
<td>16</td>
<td>21</td>
<td>23.1</td>
<td>10.7</td>
<td>0.6</td>
<td>-</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>15b</td>
<td>C-B</td>
<td>16</td>
<td>21</td>
<td>17.3</td>
<td>27.7</td>
<td>1.5</td>
<td>-</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>15c</td>
<td>C-B</td>
<td>16</td>
<td>21</td>
<td>23.7</td>
<td>26.4</td>
<td>1.5</td>
<td>-</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>17a</td>
<td>C-B</td>
<td>16</td>
<td>21</td>
<td>25.0</td>
<td>23.1</td>
<td>1.8</td>
<td>-</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>17b</td>
<td>C-B</td>
<td>16</td>
<td>21</td>
<td>16.7</td>
<td>9.1</td>
<td>1.1</td>
<td>-</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>8b</td>
<td>C-B</td>
<td>35</td>
<td>21</td>
<td>25.8</td>
<td>14.9</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>18</td>
<td>C-B</td>
<td>35</td>
<td>21</td>
<td>15.5</td>
<td>27.7</td>
<td>0.9</td>
<td>-</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>8a</td>
<td>C-B</td>
<td>41avVE</td>
<td>23</td>
<td>35.4</td>
<td>19.1</td>
<td>0.5</td>
<td>-</td>
<td>C</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>16b</td>
<td>C-B</td>
<td>41avVE</td>
<td>23</td>
<td>14.5</td>
<td>29.2</td>
<td>0.4</td>
<td>-</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>15a</td>
<td>C-B</td>
<td>41pvVJ</td>
<td>25</td>
<td>49.6</td>
<td>16.2</td>
<td>0.7</td>
<td>-</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>17d</td>
<td>C-B</td>
<td>41pvVE</td>
<td>25</td>
<td>40.0</td>
<td>-</td>
<td>0.8</td>
<td>-</td>
<td>C</td>
<td>C</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>Maneuver type</th>
<th>Location</th>
<th>V_c (km/h)</th>
<th>V_b (km/h)</th>
<th>TA (s)</th>
<th>PET (s)</th>
<th>STOPPED VEH</th>
<th>ROW</th>
<th>YIELD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaivomestarinnity</td>
<td></td>
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<tr>
<td>11</td>
<td>C-B</td>
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<td>28</td>
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<td>11.3</td>
<td>1.8</td>
<td>1.5</td>
<td>-</td>
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<td>C</td>
</tr>
<tr>
<td>16</td>
<td>C-B</td>
<td>38pvE</td>
<td>26</td>
<td>35.4</td>
<td>13.7</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
<td>C</td>
<td>B</td>
</tr>
<tr>
<td>9</td>
<td>C-B</td>
<td>38pvJ</td>
<td>36</td>
<td>27.6</td>
<td>13.7</td>
<td>-</td>
<td>0.6</td>
<td>-</td>
<td>C</td>
<td>B</td>
</tr>
<tr>
<td>12</td>
<td>C-B</td>
<td>41avOE</td>
<td>34</td>
<td>20.8</td>
<td>19.3</td>
<td>1.0</td>
<td>-</td>
<td>C</td>
<td>C</td>
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</tr>
</tbody>
</table>

The severity of the detected conflicts can be evaluated with the magnitude of the TAs or PETs and the approaching speeds. The locations are marked on appendix 4. Those preliminarily identified conflicts with TA values over 2 seconds were discarded: 2 from Tuomarilankatu and 6 from Kaivomestarinnity. In addition, Kaivomestarinnity included 2 suspected conflicts where the conflict indicators could not be calculated because of the limited vision. These seemed similar to the ones listed, and not especially severe. They were discarded because of the uncertainty. Figures 37 and 38 show conflicts that occurred during the observation period.

In almost every passing the cyclists stopped pedaling when approaching the conflict points before or instead of actually braking. As opposed to actually hitting the brakes, the gradual small decrease of speed caused by seized pedaling has not been counted as a deceleration that would constitute as a TTC value. No cyclists were detected travelling only on the carriageway. The few mopeds driving on cycle path were ignored. Less than one percent of the cyclists walked the bike when crossing the street. No conflicts between two cyclists or cyclists and pedestrians were detected.
Tuomarilantie and Tuomarilankatu

584 cyclists were counted on Tuomarilankatu and Tuomarilantie, which is an average of 53.2 cyclists per hour (appendix 5). As was expected, most of the travel for both cyclists and motor vehicles occurred along the major street (Tuomarilantie) thus avoiding the conflict points. When approaching from the side street, the intersection is probably known by many as difficult to cross since the vehicles on the major street have right of way and there are high traffic volumes. Drivers can expect to stop for the yield sign and therefore do not approach the intersection with great speed. Especially during the rush hours, the waiting area between Tuomarilantie carriageway and the pedestrian crossing was almost constantly occupied. As the approaching driver sees that the waiting area is occupied, the only options are to stop before the pedestrian crossing or on it, which is both illegal and irrational with even moderate cyclist or pedestrian volumes. This is expected, as nearing in on road capacity lowers injury severity as the speeds cannot be high. Even when stopping on the pedestrian crossing the speed cannot be great when there is a need to stop (car in the waiting area) right after it. For the cyclists, seeing the waiting area occupied and a car approaching or waiting on the other side creates a narrow corridor or, at times, an obstacle that might lower the cycling speeds.

The types of conflicts observed on the site indicate different problems than what can be seen from the occurred accidents (Figure 37). Four of the five cases on the accident data have cyclists travelling on the left side of the street, on the poor visibility location when motor vehicle enters the major street. Only two conflicts of this type were detected. Similarly, eight of the eleven conflicts have cyclist travelling on the left side of the street. Those two conflicts where cyclists are crossing the major street without right of way were especially severe.

Figure 37 Conflicts detected on Tuomarilantie and Tuomarilankatu.
The pattern of the detected conflicts was motor vehicles exiting to left from the major street (Tuomarilantie) causing conflicts with cyclists travelling on the same direction on the left side (type 16). The behavior of the drivers is explained by the gap theory: the drivers need to first find a gap from the opposite flow (major street) and only after that consider the cyclists flow. The left-turning drivers usually started crossing on a resting position (while searching for the gap). There the cyclists are on a possible blind spot while the motor vehicles are trying to swiftly get out of the way of the busy major street. Based on the conflict indicators (TA values and speeds), however, these conflicts were not especially severe. The other conflicts had considerably lower TAs and higher speeds. Often the cyclist stopped pedaling when approaching the point of conflict. At times they were not slowing down, evidently assuming the motor vehicles respect their right of way. There seems to be no confusion about the right of way. In the majority of the conflicts the drivers yielded to cyclists.

**Kirkkokatu and Kaivomestarinniitty**

433 cyclists were counted on Kirkkokatu and Kaivomestarinniitty, which is an average of 39.4 cyclists per hour (appendix 5). There were less conflicts on this site (Figure 38), and they were not as severe. Three of the four conflicts have cyclist on the left side of the street. No distinct pattern can be drawn from these conflicts related to design. Often the cyclists were crossing the street with low speeds and stopped pedaling before. The decelerations allowed either the cars to go before, or to stop and give the cyclists safe crossing. In non-conflict passages this happened usually before any conflict could develop, as is expected for most passages. In numerous safe passages and in two of the four conflicts motor vehicles gave up their right of way and yielded to crossing cyclists.

![Figure 38 Conflicts detected on Kirkkokatu and Kaivomestarinniitty.](image)

The conflicts were almost all post-encroachments. Half of them were situations where the cyclist is crossing the street and following the motor vehicle. The conflicts that have cyclist yielding are arguably of less true danger. When the cyclist yields (goes after motor vehicle), he or she is in control of the situation. Moreover, in these cases the cyclist would
have hit the motor vehicle already occupying the shared area, which is arguably less severe than a motor vehicle hitting a cyclist. When the vehicles are not on a collision path, TA cannot be used to show more about the conflicts. Though the conflict with the motor vehicle approaching the slightly raised crossing (38pvE) had quite high speed (35 km/h), the conflict did not appear especially severe, as the cyclist was following the motor vehicle.

### 4.3 Workshop

The perks of unidirectional design raised on the workshop include possibilities of using space more efficiently (especially at intersections), increased safety and efficiency at intersections and increased flow. No thoughts were raised concerning decreased safety produced inherently by unidirectional design. However, there were considerations related to the implementation of unidirectional paths. These are to some extent covered on the background information of this thesis, and their relation is discussed further in chapter 5.2.

- The amount of separation
  - Three-level
  - Cycle lanes
  - Bicycle streets/mixed traffic
  - Dealing with bus stops
  - Construction and maintenance requirements
  - Spatial requirements and ensuring sufficient width
- Signal-control (cyclist-specific)
- Bike boxes and painted lanes
- Cyclist difficult left turn
- Continuity of routes
  - Within and between districts
  - To key destinations
  - Between different street classes
  - Joining unidirectional path outside of intersections
  - Prioritize cyclist routes to cars
- Uniformity of decisions

The questionnaire posed to the participants concerning the thoughts on unidirectional solutions in Espoo provided the following results.

At the start of the workshop:
- 31 (76%) (“would apply well”)
- 8 (20%) “maybe”
- 1 (2%) “not applicable in Espoo”
- 1 (2%) “don’t know”

After the workshop:
- 25 (93%) “would apply well”
- 2 participants (7%) “maybe, needs additional research”

It is possible that the workshop itself cleared up what was meant with the question, thus reducing the negative votes. Based on these results it seems the professional community supports widely unidirectional design for Espoo.
5 Discussion

5.1 Safety assessment

The studied relationship between accidents and cyclist travel (left side of the street) is by no means a causality. It cannot be shown that the accidents occurred because of the direction of the cyclist, even though it might seem probable. The defined safety potential is based on historical data, and there has been no exposure control. To mitigate the accidents, unidirectional design is one of the possible solutions.

The reclassification of data done in this thesis was aiming mostly to reveal the hidden details within accident type 41. As the vague type 41 accounted for more than 37% of the accidents, the reclassification served a purpose of understanding additional details. Based on the accident data analysis, 27% of the cycling accidents in Espoo could have potential to be mitigated with unidirectional design. Though the number of accidents where the cyclist is travelling on the right side of the street (21%) is not considerably smaller than the left-sided accidents, it is argued here that these accidents caused by BCPs are an additional burden at the intersections. With unsignalized intersections the left-sided travel was related to 54% (43 pcs) of the accidents. Of accidents only on the near side of the intersection, the unexpected left-sided cyclist was on 60% of the cases (coming from the right). With some streets, the network requires the route flexibility provided by BCPs. In others, left-sided travel does not have to exist, unlike right-sided travel (as long as we have intersecting traffic flows). Although the proportion of BCPs necessary for the transport network is unknown (and arguable), left-sided cyclist accidents on any of them were listed as potential. Though in this thesis all of the left-sided accidents are declared as potential, it is arguable that those where the driver was turning right have the cyclist on a visible and safe position. 7% (14 pcs) of all accidents were these. The question comes down to whether it is unintuitive to have cyclist approaching from the opposite direction even when you have visibility. According to the [ref], while drivers have visibility on cyclists, they can fail to register them (Herslund and Jørgensen 2003).

When the objective is to improve safety, the question is not limited to the accident types deemed as “potential”. Solving issues on specific types might create positive as well as negative consequences to the surrounding system. Removing BCPs does not translate only to no accidents with cyclist on the left side, but they could to some extent shift somewhere else. With unidirectional design no (law-abiding) cyclists are on the blind spot of left turning vehicles, but as the cyclists are shifted to the other side of the street, they might be on the blind spot of right-turning vehicles. There might be a case to be made that it is better to have cyclists on the left turn of the driver, who has more time to physically turn towards the cyclist, and is sitting on the left side of the vehicle with better visibility. Though, in Espoo accident data the possible blind spot did not make a difference and surprisingly it was in fact slightly rarer on the right turn. It is possible that a left turn keeps the driver alert, as opposed to making a casual right turn (without that much conflict points to consider). In all turning accidents, whether or not the cyclist was on a probable blind spot (travelling on the same or opposite direction) was equally common (18 accidents each). Right turns accounted for considerably more accidents (26 pcs) than left turns (10 pcs), even though left turns are more difficult, and the driver has more to scan and focus on. Additionally, turning accidents with cyclist on the right side were singled out. They were 8% (16 pcs) of all accidents (types 16 and 35). These are not about
the directional flow, but they could be decreased also with intersection treatment. A majority (12 pcs) of these were right turns, which are shown to be dangerous on the literature. They are mostly located on larger intersections. All turning accidents (including those classified as potential, 20 pcs) total to 36 accidents, and 18% of all cycling accidents. The cyclist on the left side of the street was slightly more common, and whether the cyclist was coming from the same direction (possible blind spot) or not, made overall no difference (equal 18 accidents on both).

With unidirectional cycling the intersections become simpler and more logical with fewer conflict points. This is usually associated with increased safety, as it frees the road user’s attention to the remaining conflict points and travel directions (that do not differ from those of motor vehicles). With BCPs, the driver needs to scan both of the directions. Not having to focus on the points that have no cyclists travelling might reduce any other accident types, as well as remove the potential ones. This seems especially plausible with long term changes in the traffic culture. Further consideration reveals a possible problem. Implementing the design will inevitably come with some unwanted contraflow. The contraflow can prove to be even more unexpected than on BCPs where left-sided cyclists are regular. A purposeful unidirectional solution is bound to have less contraflow, especially when the volumes are high (Methorst et al. 2017), but the less often it occurs, the more unexpected it will be. Van Hamperen et al. (2018) observed less driver speed reduction on conflicts when a great majority of cyclists were travelling on the illegal direction of a unidirectional path. This underlines the importance of functional network planning of continuous routes which reduces cyclist illegal contraflow.

The problems with left-sided cyclists are not especially common when compared to those of Helsinki. Helsinki has a different city structure, which accounts for some of the difference. Arguably on a denser city structure the problems with BCPs will increase. Firstly, they have safety problems with frequent intersections (Cycling Embassy of Denmark 2012). Decreased space on the street area allows for less possibilities when accounting for visibility and speed reduction. In addition to the inherent unexpected travel directions, BCPs are problematic especially where they cannot be constructed to sufficient width. Narrow BCPs can increase head-on collisions and collisions with pedestrians. Espoo is described as having dense city centers on a Finnish scale. However, the density is not very high on a European scale. So far, with the city structure of Espoo, overall there has been quite much space to use for design, with for instance the recommended 3 to 3.5 meter separation verges on main streets and collectors (with vegetation). This can change locally with densifying city structure and call out for unidirectional solutions.

The potential accidents occurred on large street classes, mostly main streets, regional collectors and local collectors. The accidents are especially common with cyclist travelling along the major (priority) street, while motor vehicle is approaching from the side street (double the size of the opposite scenario). These are in line with the literature: the size of the intersection increases danger, and special care should be taken for the side street approach. Turning accidents with both road users on the major street were equally common. A large majority of the left-sided accidents occurred at give-way intersections, but also on signal-controlled intersections, which are considerably fewer. In the data, there appears to be no signal-controlled intersections where there clearly is no potential for unidirectional design. 78% (14 pcs) of all accidents on signalized intersections involved a turning motor vehicle, and 12 of those were right turns. Based on the data, uncontrolled intersections do not have a problem with BCPs, which is explained to a large extent with mixed traffic: the absence of a cycle path produces cycling on the carriageway and no
left-sided travel. The accident count of roundabouts is very low (7 pcs). Although four of these had cyclist approaching from the unexpected direction, and one was unknown, the data are too few to draw any conclusions.

On near side accidents and cyclist approaching from the left side of the street, the results indicate that the driver’s intended right turn (9 pcs) is considerably more common than a left turn (1 pcs). Though the data points are few, this is in line with the results of Räsänen and Summala (1998) where drivers were scanning less to the right when intending to make a right turn and neglecting the cyclist (that travels to an opposite direction to motor vehicles). Surprisingly, turning intentions to the right were even more common with those accidents where cyclist was coming from the left. The turning intentions should be systematically marked on the statistics for more information.

The accident data does not answer well to the question of whether BCPs on local streets in particular are bad for cycling safety, as there are few accidents overall where the cyclist is travelling along the local street. Four accidents had cyclist on left side of a local street, while 13 had no potential, and three were unknown. The low number of accidents can be a result of safety of the segregated facilities (BCPs). Then again, there are multiple local streets with cycling on the carriageway, and they produce few accidents. Nine of the non-potential accidents had cyclist on the carriageway. This implies that BCPs make little difference on local streets. The literature is overall positive on mixing cyclists with motor vehicles on local streets, as long as motor vehicle speeds are controlled, and the cycling route has no special functional requirements.

The purpose of the conflict analysis was to retrieve design aspects, not to determine whether unidirectional design would fit for the particular locations. No network considerations for the routes were done, and it might be that BCPs are necessary there. With Tuomarilantie, the buildings are on one side of the street, which might rule out unidirectional design. The results from the conflict analysis indicated a problem of left-turning vehicles which are exiting the major street and on a collision course with the cyclists travelling on the same direction. It is difficult to estimate whether the turning drivers had visibility on the cyclists. The finding can be explained by Madsen and Lahrmann (2017), according to whom the driver left turn is difficult because of blocked visibility (by vehicles going straight) and small time-gaps. Though most of the conflicts have cyclists coming from the behind. The drivers seem to have difficulties finding proper gaps, as they tend to move quickly out of the way of the opposing traffic but then need to stop abruptly before the cyclist crossing to search for another gap in the cyclist stream. The detected conflict types emphasize the importance of the waiting area also on the far side of the intersection. The waiting area on the far side is smaller than on the near side when entering the main street, due to the street’s alignment. There were two conflicts where the waiting area is also relevant, but the cyclist is travelling on the right side (and on a visible position). These situations might be deliberate and under control though they are defined as conflicts. The motorists respected cyclist right of way, and these conflicts were of smaller severity than the others. Those two conflicts with cyclists crossing the priority street without right of way were severe with low TA values and high motor vehicle speeds. According to Petzoldt et al. (2017) the speed of the approaching vehicles affects the gap acceptance behavior: the higher the cyclist speeds are, the smaller gaps drivers accept. In Tuomarilankatu, there was no recognizable pattern between the speeds of either road user and the TA values.
Tuomarilankatu revealed a possibility of tidal traffic flows explaining some of the conflicts. All but two of the detected conflicts occurred during the afternoon (or night), and directional flows were not counted. When the majority of both motor vehicles and cyclists are travelling on one direction, specific conflicts occur (in this case type 16 on the afternoon), while others do not. When there are fewer cyclists commuting to work (East), they do not cross paths as often with motor vehicles than cyclists travelling away from work (West). This poses a question whether intersections should be designed more with the direction and tidal nature of the traffic flows. Of course, this is not to say the rarer situations should be neglected. There is a positive relationship between conflicts and accidents. Though, while accidents are rare events, perhaps rare accounts of encounters between certain travel directions add up to the surprise and make the types less safe. In other words, while some conflicts are commonplace, others might occur less often because the volumes travelling in those directions are low. And when they do occur, the road users are not as prepared.

On Kaivomestarinniitty site the raised crossing for cyclists might have had an effect for safety, as no particularly severe conflicts were recognized there. In the one conflict (38pvE) the high speed of the motor vehicle on the raised crossing could have been reduced with a steeper raise. However, as raising the crossing disrupts traffic flow, and the driver had right of way on an important route, this might not be feasible. The behavior on the two conflicts and the safe passages where drivers give up their right of way is in line with the findings of Van Hamperen et al. (2017). In relation to this, Karvinen (2012) found that with cyclist crossings more often the drivers do not know their right of way than the other way around.

There is a difference whether the cyclist collides with the motor vehicle or the other way around, especially with higher speeds and complete collisions, where there is a danger of the cyclist getting run over. The severity of a conflict is not defined only by the indicator values, but also by the vulnerability of the road user. It would seem those PET values where the cyclist was travelling slowly and following the motor vehicle are not particularly severe. Most of the detected conflicts included cyclist post-encroaching a motor vehicle with low speed, even though the low PET values alone might indicate high severity. A low PET value can be misleading also as it does not account for the speed of the first vehicle. As recommended by Laureshyn et al. (2010), this is a demonstration on the importance of having some additional measures of conflict severity as opposed to only using the conflict indicators.

Head-on collisions with two-wheelers came up on the literature as causing safety issues with BCPs (Methorst et al. 2017). Unidirectional design is an inherent countermeasure for these, since the cyclists or mopeds would be travelling on the other side of the street. However, this did not show in the data from Espoo. Most of those types occurred on solitary cycle paths, and usually with mopeds. Although collisions with mopeds were plenty (18 pcs), there was virtually no head-on collisions that had to do with BCPs at intersection proximity or adjacent to streets (where unidirectional design could be used to solve the problem). There is a possibility that head-on collisions between cyclists are underrepresented, as cyclist-cyclist accidents might be in general. Though neither did the conflict analyses produce any notable cyclist-cyclist conflicts.

According to CROW (2016, p. 141), there is a relatively high number of cyclist-cyclist and cyclist-pedestrian accidents on BCPs. They can confuse pedestrians, especially at intersections and stops (City of Helsinki 2016). Pedestrian-cyclist accidents (types 74 and
79) overall were rare (5 pcs), of which those that could connect to having cyclist on the left side were non-existent. Some of the data was missing. The number of pedestrian accidents seems to be much higher in the insurance data. An underrepresentation caused by low report rate is possible also with pedestrians. The insurance data from Finland does not show differing travel directions as the problem (Utriainen 2020). However, any cyclist-pedestrian accident occurred on shared path might be reduced with unidirectional design that is by nature separated from pedestrians (at least with markings), if it is compared to a shared BCP. Creating separate quality BCPs requires much space on the street area, and when the space is scarce, unidirectional design might be the only option for separation.

5.2 Design implications

As the potential is shown mostly at intersections of larger street classes and on those with give-way (yield signs) or signal control mechanism, these are the logical candidates unidirectional design could be applied to. The higher number of motor vehicles approaching from the side street is in line with the literature (Pedler and Davies 2000) and underlines the possibility of designing the major street cycle paths unidirectional. Alternatively to unidirectional design, other means, such as deflection, raised crossings, speed bumps or stop control can force the drivers to decelerate and have the time to look right (Summala et al. 1996). In some cases, especially with much traffic, signal-control or roundabouts should be considered to replace give-way intersections. The alternative means might disrupt the flow of the side street, and still result with cyclists flowing on both directions, which means multiple conflict points for a limited amount of driver attention. Though at times this is inescapable, as BCPs are needed also for their flexibility on routes.

The application of unidirectional design should start on the network level, and only consider the potential in accordance with route continuity. People tend to choose the short routes where they see them, and if the unidirectional route is longer, more problems can occur. For the city structure, BCPs are needed when cyclists need to cross the street on situations where one is to travel a few meters along the street from one building to another (for instance with commercial zoning on one side of the street). If the necessary BCPs are made unidirectional, either frequent crossings or illegal contraflow are expected.

All turning accidents occur mostly on larger intersections. Collision with a right-turning vehicle was 2.6 times more common than with left-turning, which will remain a problem with unidirectional design. On turning accidents, the position of the cyclist did not seem to matter much. The visibility of the cyclist on the right must be ensured with adequate intersection treatment, regardless of whether cyclist is coming from a possible blind spot or not, as it had little effect on the accident count. If intersection treatment is not enough, a prohibited right turn for motor vehicles can work on some locations where it does not disrupt the traffic flow too much.

When unidirectional solutions are chosen, the safety aspects on different traffic situations are described in chapter 2.5. Raised crossings are recommended (Thomas and DeRobertis 2013; Schepers et al. 2011), but when they are not feasible, other treatment is needed. The literature is not entirely unanimous on the options with intersection treatment. It would seem that the amount of deflection should either be enough to provide a waiting area for the vehicles (2 to 5 meters, Schepers et al. 2011; CROW 2016), or none to ensure visibility between road users (Thomas and DeRobertis 2013). Obstacles on the street area need to be limited, especially on the separation verge to ensure visibility on right turns.
When approaching the intersection from the side street, also visibility on the right is important for BCPs. The current practice of city of Espoo (2010) recommends using a separation verge of 1 to 3.5 meters (varying between vegetation and pavement) on main streets and collectors and continuing its alignment as a deflection on intersections. Three meters is within the recommended range and may account for some of the safety seen in Espoo. Based on the literature, a one-meter separation verge seems to be counterproductive. As the conflicts from Tuomarilankatu demonstrated, the waiting area needs to be quite large to accommodate vehicles making the left turn. The protection is recommended also on road sections.

The conflict study intersections with hypothetical unidirectional design illustrate the increased simplicity when the conflict points from left-sided cycling are removed. Almost all of the detected conflict types on Tuomarilantie could potentially be eliminated with unidirectional design, including the poor visibility when entering from the side street, which is in most of the site’s accidents. The conflicts occurred mostly for the vehicles exiting without a proper waiting area. Also, raised crossing would not disrupt the side route considerably, as the major street has high traffic volumes, and the vehicles approaching from the side street usually have to stop anyways to look for a gap, or because the wait area is occupied by the previous vehicle. The slightly raised element on Kaivomestarinniitty had little effect on the speeds of the motor vehicles. A “half-measure” might serve a purpose there, being as the cyclists do not have right of way on the crossing and the route is important. Though, when efficiency is required from raised elements, they need to be made steep enough and visible from a distance to actually force the driver to safely stop or decelerate.

The results from the workshop were overwhelmingly supportive of unidirectional design in Espoo. This does not differ much from the general positive take of the literature. The workshop did not produce any concerns that unidirectional design would have inherent safety issues or unwanted effects. However, the achieved safety is dependent on how the design considerations are addressed. Route continuity is very important in both the literature and workshop results. The street design considerations did not differ much from those of the literature, and they have to a large extent been addressed in chapter 2.5. Ensuring width is important when considering specific design, as insufficient width is shown to decrease safety. With bus stops, emphasis needs to be on pedestrian safety as well as reducing conflicts between exiting or entering buses. Mixed traffic is a safe solution on quieter local streets, if the motor vehicle speeds are controlled. The importance of red painting with cycle lanes was raised, and that though cycle lanes have worked on some locations, they can cause perceived danger among cyclists. Having clear markings on the chosen solutions is recommended on the literature (Reynolds et al. 2009; CROW 2016), though the effect was also found negative (Schepers et al. 2011). The safety effects of cycle lanes remain somewhat mixed, though overall positive compared to no facilities. The use of bike boxes was suggested with signalized intersections. When cycle lanes are designed, the literature overall recommends advanced stop lines (bike boxes) as a safe solution used on signalized intersections, as it improves cyclist visibility (Dill et al. 2012). Cyclists’ turning or joining unidirectional paths to different design are not addressed in this thesis, nor are the issues concerning policy. Overall the workshop considerations were similar to those on the literature.

The city of Espoo needs to increase cycling volumes and modal share, but do so with design that is safe. The aspects that need to be evaluated are not only safety but also for cohesion, directness, attractiveness and comfort. These are limited with exterior factors,
such as the available space or budget. Applying “best practice” in different circumstances and under different conditions should be done with careful consideration (Wegman et al. 2012). One point of design is the dichotomy between traffic flow and safety. A manifestation of this is the use of raised crossings, which is shown to increase safety but can disrupt the flow of motor vehicles (and crossing bicycles). At times the speeds of cyclists need to be controlled. When intersections need to be designed so that the drivers have time to spot cyclists, cycling speeds also come into play. High cyclist speeds have been associated with increased injury risk (Harris et al. 2013), especially with severe injuries (CROW 2016), and smaller driver gap acceptance (Petzoldt et al. 2017). Low cyclist speeds might be an explaining factor for the safety of cycling in the Netherlands (Schepers et al. 2017b).

The literature on the effect of infrastructure design on cyclist safety is remarkably sparse, (Reynolds et al. 2009). Mulvaney et al. (2015) thought that the available data on is of low quality and could not draw any robust conclusions. Infrastructural safety studies lack standardized, transferable data on exposure to risk (DiGioia et al. 2017; Thomas and DeRobertis 2013). The literature found in this thesis did not differentiate much between signalized and unsignalized intersections. The safety results found from different cities and countries have varying design practices, city structures, traffic cultures, volumes and speeds. Because of the differing local conditions, research knowledge is difficult to generalize (Wegman et al. 2012). While it is difficult to prove causalities between any street attributes and accidents, similarly it is difficult determine which solutions best address certain dangers. The chosen solution is always only one way of counter-measuring, while others might do as well. Consequentially, any results got from one design might not be completely applicable to the case of Espoo, and with the varying conditions (that an accident is a sum of) it is difficult to draw solid conclusions that any design is inherently “good” or “bad”. Moreover, the conditions of Espoo are changing constantly, as the city is developed.

5.3 Data collection

Cycling accidents have a low reporting rate compared to other modes (Wegman et al. 2012). The overall coverage of the official Finnish accident statistics is estimated to be around 30% and suspected to be especially low on single-bicycle accidents (Destia 2019). With single-bike accidents, as the data included only three cases over 10 years, the coverage appears to be close to non-existent. Insurance data suggests that cycling accidents are fourfold compared to the numbers on police reports FTIA (2014a, p. 30). According to Utriainen (2020) in Finland 19% of seriously injured cyclists are recorded in the police reports while 81% end up only in the medical data. Further study and classification on hospital emergency room or insurance data could provide additional information on cycling safety. Though, the medical data does not include the important characteristics for design (such as accurate location and accident type), thus it is not of use for the purposes of this thesis. For the relevance of unidirectional cycling, the research would need to focus on those accidents that included multiple road users and did not occur on solitary cycle paths.

As a side note, the proportion of moped-cyclist accidents on cycle paths, 9% (18 pcs), is quite high considering the low number of mopeds in traffic. On average, mopeds have multiple times the monetary value of bicycles and are equipped with mandatory traffic insurance, which might lead to cyclist-moped accidents having a higher report rate than cyclist-cyclist accidents. Though with higher speeds and mass differences mopeds are
also more prone to accident, especially to more severe cases. As bicycles are getting more valuable with the popularity increase of electric bicycles, the accident report rates might increase.

The official statistics compiling system could be made more considerate toward cycling accidents. All accidents have 13 classes (crossing accident, rear-end accident, deer accident etc.) of which “cycling accident” is only one and the rest concern motor vehicles. Though, the same information is included in the accident type classification. The official accident types include only 7 types that are cyclist specific (15, 16, 34, 35, 41, 42 and 55). The methodology of this thesis was heavily fixed upon type 41 because of its dominance and the vagueness: it does not include cycling directions, the side of the street or near or far side of the intersection. Knowing cycling direction, side of the street or side of the intersection would be useful, but only two is needed to deduce the third. Neither does the classification include right of ways or initial travel directions of cyclists when they are turning.

The marking of the accidents should be more careful. Majority of the “other accident” types (9, 29, 39, 49, 59 and 99) turned out to be some of the actual types when looked in more detail. The rework on this thesis reduced the number of “other accidents” from 38 to 13. There was a systematic error in the marking where motor vehicles crashing on the near side of three-leg intersections were marked as turning types (15, 16, 34 or 35). This is not the intent of the classification, as no turn had yet occurred, and they belong in class 41 (or the more detailed classes used in this thesis). Though, this practice did produce hidden information on the motorist’s turning intentions. The police report descriptions are not entirely uniform. They differ somewhat annually, and some cases are missing non-standardized information that other cases include. Some of the information was incorrectly marked in the statistics, as was revealed by studying the detailed description and by looking at the site’s Street view (Google 2019), Street Smart (Cyclomedia 2020) and orthophotos taken in the year of the accident (Google 2019; City of Espoo 2019f).

Accident data study methods should focus on injury severity (Thomas and DeRobertis 2013). It might be misleading to clump all injuries into one category with no considerations of the severity. The severity might often be difficult to determine on the accident site before any medical examination. However, even some rough classification, for instance a scale from 1 (no medical attention needed) to 4 (ambulance required), would provide information on the conditions the severe accidents occurred. Related to severity, the accident statistics could systematically mark motor vehicle type to yield more information on their problems, with larger vehicles in particular, as they are known to be dangerous.

The modified classification turned out to be quite detailed in relation to the available data, resulting with some accident types to have few or no data points. In the future, a simpler classification can be more applicable. If the idea of the new classification is considered purposeful elsewhere, a simplification could be included in the system with a small change: by including some of the desired aspects (cyclist travel direction, near/far side of intersection, right of way, cyclist turn) and continuing types from 42 to 48 and renaming type 43 (perhaps to 98 since it is a special case although crossing traffic). If the right of ways or travel directions are not desired to be separated into classes, the data could still be systematically marked on the official police reports (dataset 1). For unidirectional design, the most important factor is the direction of the cyclist.
The results of the conflict analyses, particularly the post-encroachments, underline the importance of not relying on only one conflict indicator. A traffic event with relatively low PET or TTC can turn out to be safer, depending on which road user travels first, and what are the speeds. The respect of right of way is relevant information, as it can tell something of how severe the collision would have been. When the cyclist goes after, he or she is in control, and by default the accident would be less severe when cyclist hits a motor vehicle than the other way around.

The validity and reliability of conflict methods have been debated. There are differing views as to the extent to which the used methods of detecting conflicts accurately represent real traffic situations, listed for instance by Silla (2016, p. 19). The nature of the methodology was qualitative for the purposes of this thesis, that were not to study these specific intersections but get results for the whole question of intersection treatment. To produce quantitative methodology for any specific accident-prone site, longer recordings are needed. For longer conflict analyses, there is technology for automated video analysis which will enable an efficient use of resources (Madsen and Lahrmann 2017; Essa and Sayed 2018; Laureshyn 2010, for instance). Automated video analysis and a framework around relevant indicators help elaborate on the validity and reliability (Laureshyn et al. 2010). As discussed above, for conflict analyses, the calculated volumes for each mode from each direction could be used to eliminate the effect for conflicts occurring because of certain flows and not design itself. As the directional volumes of cyclist or motor vehicle volumes were not measured, tidal volumes can in part explain the results with left-turning vehicles. Though the measure time (8-19) included a large portion of the morning and afternoon traffic, more volumes (and conflicts) were detected on the latter period (appendix 5). The measurement errors are detailed out in chapter 3.2.3.
6 Conclusions

In the literature, unidirectional design is generally considered to increase intersection safety (Thomas and DeRobertis 2013; Schepers et al. 2017b). The inherent safety function of unidirectional design at intersections, as opposed to bidirectional paths, is that cyclists are not travelling in the opposite direction to motor vehicles: on the left side of the street. While all left-sided travel can be addressed as a problem with bidirectional paths, the clearest cases are those where the driver is approaching the intersection from the secondary street and colliding on the near side, while about to turn right without paying attention to the cyclist coming from right. The safety assessment of unidirectional cycle paths was done for the city of Espoo to determine the extent and qualities of accidents including the cyclists’ left-sided travel.

In Espoo, 15% of all the accidents leading to bodily injuries included a cyclist (2009-2018). The accident data analysis provided overall results: 27% (53 pcs) of all cycling accidents occurred on a position where the cyclist was approaching an intersection on the left side of the street when colliding with another road user. An additional 8% of accidents occurred with an unknown side of the street. The left-sided travel was not much more common the right-sided (21%). On unsignalized intersections with cyclist on the cycle path, left-sided travel adds up to 54%. When looking only at the near side of the intersection (crossing directions), the unexpected cyclist approaching from the right was in 60% of the accidents, which is a recognizable majority, though the numbers were higher on the comparison cities: 70%, 75% and 85% (Räsänen and Summala 1998; Härme 2018; Pasanen and Räsänen 1999).

The accidents with a left-sided cyclist are clearly not as common as in Helsinki. However, as the city structure of Espoo is getting denser, the need for unidirectional design could develop further. Bidirectional paths (BCPs) are least safe in tight urban spots with multiple crossings, poor visibility and insufficient width. The current city structure of Espoo has allowed for quite safe design of intersections, with for instance 3 to 3.5 meter separation verges on collectors and main streets. With a dense city structure this might not be an option, which would further increase the need for unidirectional solutions. Moreover, the concentration of the city structure allows for cycling to increase as a mode, which poses more requirements for the cycling infrastructure. When separation from pedestrians is needed and space is scarce, unidirectional design might be the only option. Conversely, it could be argued that while densification is occurring, the width of the street area should not be bargained for.

Since the left-sided travel in many cases does not have to exist, it can be seen as an additional burden for the intersection. The found potential accident types could be solved with unidirectional design alone, as ideally the cyclists would not travel on such locations, leading to none of such accidents. Unidirectional design simplifies the intersection areas by removing conflict points. A case can be made that unidirectional cycling improves safety also for other accident types since the removed possibilities of a conflict free up the road user’s attention for the remaining conflict points. However, since the cyclists would then travel on the other side of the street, they could to some extent shift the accidents to the other types.

According to multiple studies, cycling accidents occur mostly at intersections of larger streets (Harris et al. 2013; Reynolds et al. 2009), and Espoo is no exception. The potential
of unidirectional design does not differ from this pattern: the most left-sided travel accidents are on regional collectors, main streets and local collectors. Cycling accidents occur more often when the cyclist has the right of way and is travelling along the major street the motor vehicle is either entering to or exiting from. The most potential is on unsignalized (give-way) intersections with yield sign, followed by signal-controlled intersections, with mostly turning accident types. Unidirectional design can be a part of the solution at signalized intersections, such as the Danish type intersection studied by Jensen (2008). Usually these major intersections have also other possibilities of increasing the safety of cyclists, such as bike boxes (Dill et al. 2012) and cyclist-specific signal cycles.

Because of the nature of unidirectional design, the potential found on street classes should be considered only in the terms first laid out by the network requirements. To avoid increased crossing or illegal contraflow on unidirectional paths, network route considerations are necessary. Though bidirectional cycle paths (BCPs) appear to be less safe at intersections, they do offer a wider flexibility to cyclist route choice and for high tidal cyclist volumes (as the whole width can be utilized for one direction). To enable continuous cycling routes, not all of the paths can be made unidirectional. BCPs can be used with heavy one-sided commercial zoning, where unidirectional design would increase illegal contraflow or the need to cross. Also, the shortcomings of BCPs are fewer with fewer crossing streets (Cycling Embassy of Denmark 2012). The importance of ensuring route continuity was also emphasized on the workshop. CROW (2016) recommends BCPs to be used when network benefits outmatch the lost safety on intersections. When BCPs are chosen, intersection treatment is arguably even more important. Especially the visibility from the side street to the right should be ensured (Pedler and Davies 2000).

The high risk of cycling accidents with right turning vehicles is established on the literature (Cycling Embassy of Denmark 2012; Pucher and Buehler 2008). Turning accidents were singled out from the accident analysis. The data indicates that the place or travel direction of the cyclist does not matter as much as the motor vehicle turning direction: right turn accidents were 2.6 times more common than left turns. Whether the cyclist was approaching from the same or opposite direction made little difference, just as whether the cyclist was on the left side of the street or not. Adequate visibility needs to be ensured, especially with the right turning vehicles. This can be achieved with intersection treatment.

Since accidents are rare events a conflict method was used as a different approach. The conflict analyses of the two sites were aiming to reveal intersection treatment aspects that are not visible on the accident data. Those conflicts observed on Tuomarilantie would be solved with unidirectional flow alone, as all but two of those cyclists were travelling on the left side of the street. The results emphasized the importance of deflecting the cycle path to create designated waiting areas at intersections, particularly after a left turn from busy the major street. It is difficult to say, whether the left-turning drivers had vision on the cyclists or not. It might be that even with adequate vision the turn must be completed swiftly to fit the small time gaps from the oncoming opposite traffic flows. Those conflicts were not especially severe, and the left-turns were not common on the accident data. The waiting area is larger for the entering vehicles, which is also evidently important because of the visibility issues.

The factors affecting safety when choosing unidirectional solutions are described in the chapter 2.5, both for road sections and intersections. The results from of the workshop provided professional and cyclists’ view on the issue. The workshop considerations did
not differ greatly of those found on the literature. The input was overwhelmingly positive towards the idea of Espoo incorporating unidirectional solutions into their design practice. Safe intersection design aims to calming traffic speeds and ensuring visibility between road users. At times, cyclists’ speeds should be controlled. Low cyclist speeds are among the top risk factors explaining cycling safety in the Netherlands (Schepers et al. 2017b). While some problems can be diminished with unidirectional design alone, intersection treatment is important for others. The described ideas behind the treatments are, to some extent, applicable to BCPs, especially for turning accidents regardless of the travel directions.

The literature and European practices have differing views on whether to deflect the cycle path on intersections, and it would seem this has not been studied in Finland. On one hand deflection creates a designated waiting area, which sequences the conflicts, allows road users time to react and can make the driver physically turn towards the cyclist before their travel paths cross. Close-by cycle paths ensure better visibility, especially with large right-turning vehicles (that are an elevated danger and cannot utilize a standard waiting area of 2 to 5 meters provided with deflection). It would seem no “half-measures” are adequate: deflection should be wide enough to create the waiting areas, or none to maintain the visibility. With a small deflection there is the danger of getting worst from both worlds: decreased safety without a waiting area, and some additional width requirements from the street area.

Separation from motor vehicles is usually the safe way to design cycling facilities (Thomas and DeRobertis 2013; CROW 2016). Because the disrupting effect raised crossings can have at intersections, the amount of separation is recommended based on the need: traffic volumes and speeds, available resources and the functional requirements for the facility. Cycle lanes have mixed results, but overall, they seem to increase safety somewhat as opposed to no facilities. They are recommended on streets with moderate traffic. The literature overall supports the use of advanced stop lines (bike boxes) with cycle lanes at signalized intersections, as they place the cyclist in front of the motor vehicles, thus increasing visibility, especially with right-turning vehicles. Cycle lanes should not be used on roundabouts (Reynolds et al. 2009).

For road sections, separation and adequate width increase safety. In addition to safety-reasons, the width is chosen for the functional requirements of the route and whether overtaking is desired. Because of dooring accidents, cycle lanes should be avoided on parking lanes by removing parking or by diverging the cycle path on the right side. If this is not possible, they need to be aligned to a safe distance from the parked vehicles. Separating the road sections further away from motor vehicles exposes cyclists to less air pollution, which is associated with even more health issues than collisions. Mixed traffic is not a problem on quiet local streets if the motor vehicle speeds are controlled (mainly by width) and the function of the cycle path does not require separate facilities. Based on the accident data, the local streets had little accidents overall. One-way streets turned into contraflow for cyclists seems to be a safe solution (ITF 2013; Vandenbulcke et al. 2014).

In the accident analysis, cyclists colliding with pedestrians or other cyclists had no apparent relevance for unidirectional design, as they were rare and occurred mostly on solitary paths. Though the underrepresentation of accidents between vulnerable road users is known to be high. Generally, unidirectional facilities need less space and can be a solution to separating pedestrians. For safety reasons, pedestrians should be separated on urban
environments when the volumes require it, since the needs for walking are so different to cycling.

The quality of a design is determined by the extents to which it satisfies the five requirements for cycling: cohesion, directness, attractiveness, safety and comfort (CROW 2016). With the results combined with the knowledge from the literature it can be concluded that unidirectional design could be used as a countermeasure to the safety issues on the described traffic situations, if implemented purposefully. Though the unexpected travel directions were not a very large majority (54% or 60% depending on the situation), they could increase as cycling is increased. When the city structure becomes denser, the accidents with BCPs could increase, as insufficiently wide BCPs cause additional problems. The question of specific solutions comes often down to whether to separate cyclists from the motor vehicles with only paint and street markings, or to constructing a raised cycle track, and how much space on the street area is available for the track to be deflected for safety purposes. When the functional and safety requirements are high, unidirectional paths can be done with a high quality three-level separation, from also pedestrians. The costs depend on the chosen solution and the conditions: whether the space is available or if a renovation is needed. When a street is renovated anyways, the additional costs can be small.

Coherence of the design solutions in an area is important. If the qualities of the infrastructure vary too much, they can lead to unwanted cyclist behavior, namely confusion of right of way. With deflection, for instance, the street area that is required is surely not found on all locations. On the other hand, the safety of a solution should not be bargained for the sake of uniformity, and quality solutions are recommended rather than having lengthy stretches of infrastructure (Vandenbulcke et al. 2014). The quality of a chosen solution needs to fit for the purpose. Cycle lanes can work as a temporary solution for the less urgent locations and enable the continuity of the routes with smaller costs (Cycling Embassy of Denmark 2012). Though, there the width needs to be available when the cycle lane is upgraded to cycle track (as cycle lanes do not need as much width). Unidirectional cycling facilities can be a solution that increases safety without requiring additional space on the street area. Usually this means turning a unilateral BCP into bilateral unidirectional paths.

This thesis explored the extent and qualities of current BCP related accidents in terms of traffic environments. Though the problems are not very vast, unidirectional design could work to solve them, as it has been shown to increase safety. Moreover, it is plausible that as the city structure densifies, the issues related to BCPs could start to increase. Infrastructure design is, however, only one way to increase safety. Safety is a sum of mutually intertwined factors, such as land use and transport planning, policy, legislation, and culture. It is never known whether a specific accident occurred because of the position of the cyclist or for other reasons such as lacking visibility, construction flaws, travel speeds or human errors. An accident is a product of all the conditions, and accidents can be reduced with a variety of countermeasures, of which unidirectional design is one. Though, as is argued in this thesis, unidirectional solutions require less of the other countermeasures than are needed on BCPs. There is not much to be lost with unidirectional design, as long as the routes are planned continuous.

For future research, the potential accidents in Espoo could be narrowed further by eliminating those bidirectional paths that are key for route selection (and should not be made unidirectional). A GIS analysis could be done to compare the locations discovered here
to a list of possible unidirectional locations. It would be interesting to see whether the problems with BCPs cluster to dense urban environments more than cycling accidents overall. The safety effect of cycle lanes and deflection at intersections could be studied further. Because of the great effect of local conditions, local studies could help understand the characteristics of Espoo. Design should be an iterative process where modifications are made based on the results from previous solutions. When unidirectional cycling is implemented, controlled before-after studies done, with for instance a conflict analyses, could yield information on the specific safety effects. With any intersection design, making conflict point analyses accompanied with estimated traffic flows could help to understand the points of interest and make the design safer with small additional costs.
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Appendix

Appendix 1. Illustrated accident type catalog.

8 Liikenneonnettomuustyyppikuvasto

0 Samat ajopuunnat (mikäli ajoneuvoista ei ollut kääntymässä)

1 Samat ajopuunnat (lokken ajoneuvoilla tai kääntymässä)

2 Vastakkaiset ajopuunnat (kantamaan onnettomuus)

3 Vastakkaiset ajopuunnat (lokken ajoneuvoilla tai kääntymässä)

4 Riistaväylä ajopuunnat

5 Riistaväylä ajopuunnat (lokkien ajoneuvoilla tai kääntymässä)

6 Jalkakulkui onnettomuus (surjaistut)

7 Jalkakulkujan onnettomuus (muulla kuin surjaistut)

8 Tietää surjautuminen

9 Muu onnettomus
Appendix 2. Spatial locations of cycling accidents from Espoo city centers during 2009-2018. Red indicates death, blue injury (at least 2 occurrences) and yellow material damage (occurrences: at least 5 material damage or 1 injury and 4 material damage). The accidents are depicted in the most severe manner: red dots can include injuries and material damage, and blue dots can include material damage. (Destia 2019).

Appendix 2.1. Matinkylä-Olari.

Appendix 2.2. Leppävaara.
Appendix 2.3. Espoon keskus.

Appendix 2.4. Tapiola-Otaniemi.
Appendix 2.5. Espoonlahti.
Appendix 3. Criteria for choosing conflict study locations. (Destia 2019; City of Espoo 2019f; City of Espoo 2019b). The measured AAWTs (annual average weekday travel) are not entirely comparable since some of them were measured at different years (range from 2007 to 2018).

<table>
<thead>
<tr>
<th>Location</th>
<th>AAWT (secondary street)</th>
<th>Number of all accidents 2008-2018 (Accident type)</th>
<th>Visiblity issues</th>
<th>Speed limit, main street (km/h)</th>
<th>Cycling distance to train station (boardings)</th>
<th>Connection importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>KIRKKOJÄRVEN-TIE X KOTIKYLÄNTIE</td>
<td>7500</td>
<td>2 (41)</td>
<td>No</td>
<td>50</td>
<td>550 (5100)</td>
<td>Very high, planned superhighway</td>
</tr>
<tr>
<td>SÄTERINKATU X HUVILINNANTIE</td>
<td>3900</td>
<td>2 (41)</td>
<td>Yes</td>
<td>40</td>
<td>1000 (12400)</td>
<td>Secondary</td>
</tr>
<tr>
<td>FRIISINMÄENTIE X KIRKKONUMMENTIE</td>
<td>5300</td>
<td>1 (41)</td>
<td>No</td>
<td>40</td>
<td>1600 (12400)</td>
<td>High</td>
</tr>
<tr>
<td>KIRKKOKATU X KAIVOMESTARINNIITTY</td>
<td>13500</td>
<td>3 (30)</td>
<td>No</td>
<td>30</td>
<td>700 (5100)</td>
<td>High</td>
</tr>
<tr>
<td>NUIJALANTIE X VITIKKA</td>
<td>6800</td>
<td>2 (15)</td>
<td>No</td>
<td>40</td>
<td>1300 (1100)</td>
<td>High</td>
</tr>
<tr>
<td>KILONPUISTON-KATU X VANHARAIDE</td>
<td>4600</td>
<td>2 (41)</td>
<td>No</td>
<td>40</td>
<td>130 (2300)</td>
<td>High</td>
</tr>
<tr>
<td>TUOMARILANTIE X TUOMARILANKATU</td>
<td>15000 (4400)</td>
<td>9 (41,16)</td>
<td>Yes</td>
<td>50</td>
<td>230 (1900)</td>
<td>High</td>
</tr>
<tr>
<td>TUOMARILANTIE X TUOMARILARNINNE</td>
<td>15000</td>
<td>1</td>
<td>Yes</td>
<td>50</td>
<td>700 (1900)</td>
<td>Secondary</td>
</tr>
</tbody>
</table>
Appendix 4. Conflict identification sheets for distance measurement. The distances were used to attain the conflict indicator values.

Appendix 4.1 Model of Tuomarilantie and Tuomarilankatu

Appendix 4.2 Model of Kirkkokatu and Kaivomestarinniitty.
Appendix 5. Overall cyclist volumes counted during the conflict analyses.

Appendix 5.1. Tuomarilankatu site.

![Tuomarilankatu cyclist volumes](chart)

Appendix 5.2. Kaivomestarinniitty site.

![Kaivomestarinniitty cyclist volumes](chart)
Appendix 6. Detailed accident data graphs.
Appendix 6.1. The street class is the one the cycle path is adjacent to. The marked class is that of the initial travel right until the location of the accident.

Appendix 6.3 Unidirectional design potential accidents with accident type and intersection type.
Appendix 6.3 Accidents with potential for unidirectional design by accident type and street class.

<table>
<thead>
<tr>
<th>Street Class Combination</th>
<th>55pvVP</th>
<th>18pvP</th>
<th>18pvE</th>
<th>18avE</th>
<th>41pvVE</th>
<th>41pvVj</th>
<th>41avVJ</th>
<th>41avVE</th>
<th>17pvE</th>
<th>17avE</th>
<th>34</th>
<th>16</th>
<th>35</th>
<th>15</th>
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<tbody>
<tr>
<td>Regional collector/Regional collector</td>
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<td>Main street/Main street</td>
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<td>Local collector/Local collector</td>
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<td>Regional collector/Local street</td>
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<tr>
<td>Motorway/Motorway</td>
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**Accidents with unidirectional potential by street class, Cyclist/Motor vehicle (69 pcs)**