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Chapter 8 Cyclists' interactions with other road users from a safety perspective

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Abstract

This chapter provides an overview of the literature about selected interactions between cyclists, pedestrians, motorists, heavy-duty vehicles, busses, pedestrians, and other cyclists in urban areas. Hydén's Safety Pyramid is used as a framework for organizing interactions as frequent, inconsequential encounters, potential, slight and serious conflicts or crashes with varying levels of severity. The interactions are organized in this chapter by where they occur and the interacting road user. First, cyclists' interactions on road segments are investigated, focusing on cyclist-pedestrian interactions, interactions between cyclists and passing motorists, and interactions at bus stops. Interactions that take place at intersections are then explored and the gap acceptance of cyclists and motorists and the problematic interactions between cyclists and heavy-duty vehicles are examined. Finally, a short overview of interactions in shared space is given. Most of the literature concerns dangerous interactions between cyclists and other road users or those at the top of Hydén's Safety Pyramid. Fewer studies were found that investigate normal encounters and the potential benefits of interacting. The chapter concludes with a discussion about the mechanisms behind dangerous interactions in general and what can be done by urban and infrastructure planners, traffic and vehicle engineers, and developers of technologies to transform dangerous interactions into normal encounters.

Keywords: Cycling, Bicycle traffic, Cyclists, Urban traffic, Road user interactions, Traffic safety, Road safety

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Introduction

How a cyclist interacts with other road users and his or her environment has an enormous impact on the cycling experience. Both the perceived and objective safety, or lack thereof, as well as the efficiency, comfort, and enjoyment of cycling are all impacted by the frequency and characteristics of cyclists' interactions with others. Infrastructure planning and design play a pivotal role in shaping interactions experienced by cyclists while the experience and outcome of each interaction is influences by the type of interacting partner.

Christer Hydén (1987) proposed the well-known Safety Pyramid that describes the relationship between the frequency and severity of encounters, conflicts, or crashes between road users (see Figure 1). The large bottom section of the pyramid represents normal interactions between road users, referred to as encounters. These types of events are very frequent and do not pose any danger to either of the interacting parties. Positioned above normal encounters are potential, slight, and serious conflicts, which in this order decrease in frequency while increasing in seriousness. At the top of the pyramid are crashes, which are relatively rare events in comparison to encounters or conflicts. This theory was extended upon by many (mainly Swedish) researchers to form the Traffic Conflict Technique, which can be used to infer the number of infrequent, severe events based on the observation of different types of more frequent conflicts (Laureshyn & Várhelyi, 2018).

Figure 1: Christer Hydén's Safety Pyramid (Figure from Laureshyn & Várhelyi (2018))

One important implication of the Safety Pyramid theory is that the majority of interactions between road users are not dangerous. These encounters can even add value to a cyclist's journey through the city. One of the positive aspects of cycling in comparison to traveling by private automobile is the opportunity for the cyclist to interact with his or her environment and communicate with other people while moving in the urban environment. During her interviews in the cycling metropolitan Copenhagen, Freudendal-Pedersen noted that many cyclists report "smelling, hearing, and feeling the city is different when you "are not caged in a metal box." " (2015, p. 37).

Nevertheless, cyclists undoubtedly bear a disproportionately large burden in terms of traffic injuries and fatalities at the top of the pyramid. In the European Union, for example, cyclists account for a total of 8 % of road fatalities (European Road Safety Observatory, 2018), while at the same time constituting only 2 % of all person kilometers (Steenberghen et al., 2017). If one looks at the causation of cyclist crashes in terms of road user behavior, it is clear that the cyclists themselves are not usually at fault. For example, in Germany, 75 % and 79 % of collisions between a bicycle and a private car or truck were primarily caused by the motor vehicle driver, respectively (German Federal Ministry of Transport, 2012).

Several methods are useful in studying dangerous interactions between road users. Crash data, either from police reports or the reconstruction of collision scenes, and hospital records provide insight into cyclist crashes. It can be difficult to draw overarching conclusions from crash data because of the relatively low frequency of events and the corresponding long observation times necessary to collect adequate sample sizes. According to the Safety Pyramid theory, there is a relationship between the frequency of potential, slight and serious conflicts, and the occurrence of crashes. Based on this proposition, many researchers have focused on the investigation of conflicts and near misses to gain insight into safety-related problems. Critical incidents are tracked and mapped on a large-scale in projects such as SimRa (Karakaya et al., 2020) and BikeMaps (Nelson et al., 2015). A final method is to ask people through surveys or interviews about their experiences as cyclists interacting with other road users.

Depending on many factors, such as urban planning, road infrastructure design, traffic laws, culture, norms, and modal split, the dominating interactions of cyclists differ across cities and countries. In most places, the vast majority of interactions, and thus conflicts and crashes, experienced by cyclists are with motorists. In 2020, across Europe, 83% of cyclist fatalities resulting from a crash with another road user followed a collision with a motor vehicle (53 % with a car, 7 % with a bus, and 13 % with a truck) (Adminaité-Fodor and Jost, 2020). Fatal crashes with other cyclists accounted for only 1 % of cyclist deaths while crashes with pedestrians led to less than 1 % of all cyclist deaths. However, near misses and non-fatal crashes with pedestrians account for between 1.2 % and 6.4 % of all incidents in the reviewed literature (O'Hern and Oxley, 2019; Poulos et al., 2015). These numbers vary drastically by country.

Not only traffic safety but also traffic flow and efficiency are regulated by road user interactions. This is especially true in urban areas where many people and modes of transport come together in a smaller area. Bicycle traffic, particularly in countries with a high modal split of cycling, can have an important impact on the overall traffic flow and efficiency. This effect is most pronounced at intersections, where streams of bicycle traffic interact with and influence the flow of other modes. For example, a flow of 600 bicycles/hour on one intersection approach can reduce the capacity of right-turning motor vehicle traffic on the same approach by approximately 50 % and of left-turning vehicles on the opposite approach by nearly 65 % (Grigoropoulos et al., 2022) in right-hand traffic. Not only the presence of bicycle traffic but also the behavior of each cyclist and the methods for interaction between different road users are hypothesized to impact overall efficiency.

A good deal of research power has gone into quantifying and mathematically modeling the interactions of cyclists with other cyclists, pedestrians, and motorists to create realistic microscopic traffic simulations. These tools are used to virtually design, test, and evaluate road infrastructure and traffic control measures. If the behavior models, and specifically the interaction models, that underpin microscopic traffic simulation do not reflect the actual behavior of all types of road users, the results of simulation studies will lack realism and accuracy (Twaddle et al., 2014). This body of research offers a pool of knowledge about cyclists' normal, non-critical encounters.

In this chapter, the interactions between cyclists and other road users are explored by focusing on different components of the urban road network. I begin with an analysis of interactions on road segments, followed by an examination of interactions at intersections, and conclude with a short review of interactions in shared spaces. An overview of the findings of peer-reviewed papers that explore cyclists' encounters, conflicts, and crashes with pedestrians, motorists, busses, and other cyclists is presented and a link between the interaction and the risk to cyclists is assessed. Selected reports that are deemed to be of high quality are included in the literature review. Research gaps are noted and topics for future research are identified.

Interactions on road segments

Road segments are stretches of roads between intersections on which road users generally move longitudinally in one of potentially two directions of travel. According to the European Road Safety Observatory, 64 % of cyclist fatalities in Europe occur on road segments (European Commission, 2020a). For comparison, 81 % of pedestrian fatalities (European Commission, 2020b) and 82 % of car occupant fatalities (European Commission, 2021) occur on road segments in Europe.

Depending on the infrastructure design and modal split, cyclists face interactions with different road users. If bicycle traffic is guided on the roadway, either using marked bicycle lanes or mixed traffic roadways, cyclists will interact mainly with motorists, heavy-duty vehicles, busses, and other cyclists. Interactions with pedestrians and other cyclists dominate on physically separated bicycle infrastructure, shared paths, and sidewalks. In this section, literature on the interactions between cyclists and pedestrians, busses, motorists, and other cyclists are summarized. Particular attention is placed on interactions that are risky to cyclists or have a significant impact on traffic flow and efficiency.

Pedestrians

Interactions between cyclists and pedestrians occur when bicycle traffic is physically separated from motor vehicles and cyclists are relocated to paths shared with or adjacent to pedestrian traffic. Shared-use sidewalks and pathways are infrastructures that are intended for use by both cyclists and pedestrians without any separation between the two modes. Segregated facilities, on the other hand, allocate space to each road user group using surface markings or different building materials. The majority of the literature found in this review is focused on the occurrence of near misses or crashes between pedestrians and cyclists. Very little was found concerning the benefits of interaction and the value of personal encounters in the cycling experience.

Researchers in the German city of Berlin found that 75 % of bicycle-pedestrian crashes took place between, rather than at, intersections (Schreiber, 2013). Similarly, a study in Finland indicated that most near misses and collisions between cyclists and pedestrians happen when the road users move in the same direction (Mesimäki and Luoma, 2021). The infrastructure characteristics, particularly the width and the separation between cyclists and pedestrians, have a large impact on the safety and comfort of both types of road users. Incidents are much more likely to occur on shared-use rather than separated facilities (Mesimäki and Luoma, 2021; Poulos et al., 2015). Poulos et al. (2015) found the crash rate for cyclists riding on pedestrian paths to be 26.4 crashes per 1000 h, which is considerably higher than for other road environments. For example, the crash rate was found to be 8.8

crashes per 1000 h on shared pedestrian and bicycle paths, 5.8 crashes per 1000 h on cycle lanes, and 4.7 crashes per 1000 h on roadways.

Hatfield & Prabhakharan (2016) looked at the behavior of pedestrians and cyclists on shared-use facilities and found that cyclists were more likely to follow the left-hand rule (in Australia) than pedestrians and typically gave way to pedestrians. However, passing on the wrong side, passing too close and too quickly, and not giving warning were all observed in the study. Mesimäki & Luoma (2021) found that both pedestrians and cyclists feel less safe on shared-use facilities and were less happy to ride or walk on them compared to paths segregating road users.

A major source of conflict between cyclists and pedestrians is their differing patterns of behavior. Cyclists typically use their bicycles to travel quickly along a specific route. Pedestrians, on the other hand, are not always motivated by reaching their destination as quickly as possible and tend to change their path, direction, and speed spontaneously. In addition, pedestrians are more likely to be distracted, for example by conversations, the use of mobile phones, or by listening to music (Hatfield and Prabhakharan, 2016). Likely because of these differences in behavior, cyclists can experience anger towards pedestrians. Marín Puchades et al. (2017) found that cyclists' anger towards pedestrians was associated with an increased likelihood for near misses with this type of road user. Furthermore, cyclists tend to blame pedestrians more for a conflict on shared-use infrastructure than they do for a conflict at an intersection or on a sidewalk, where the pedestrian is perceived as having the right-of-way (Paschalidis et al., 2016).

Busses

Busses create unique interaction constellations for cyclists because of their regular stops, which tend to be located on road segments. Researchers have noted an increased risk of injury to cyclists when a bus stop is present (Heydari et al., 2017; Osama and Sayed, 2017; Strauss et al., 2013). However, the number of incidents at bus stop zones is relatively low. For example, 1.1 % of all personal injuries registered in Germany in 2018 happened at a bus stop (Berger et al., 2020).

Depending on the location and design of the bus stop and the type of cycling facility, cyclists encounter different types of interactions. A bus stop is a space designated for waiting, boarding, and alighting transit passengers and can be integrated into the sidewalk, a road median, or on a dedicated

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boarding island. The cycling infrastructure, on the other hand, can either be on-road or physically separated. There is a wide range of solutions for combining cycling and bus infrastructure. While it is not possible to delineate and discuss all the possibilities in this chapter, some of the most common solutions are summarized and points for (dangerous) interactions are discussed and depicted in Figure 2:

a. **Physically separated cycling facility**: The cycling facility is located between the sidewalk and the waiting area of the bus stop or between the bus stop and the roadway at the edge of the sidewalk area. In either situation, cyclists and bus passengers must interact. Afghari et al. (2014) found that cyclists tend to maintain their speed and do not perform evasive actions to avoid pedestrians at bus stops. Pedestrians on the other hand were found to reduce their speed and move out of the way of approaching cyclists. Greenshields et al. (2018) reported that the most common causes of serious conflicts between cyclists and pedestrians on this type of facility were caused by inattentiveness of the pedestrians, lack of space, crowding, visibility problems, and other features that restrained movement at the bus stop.

b. **On-road cycling facility**: A break in on-road bicycle lanes allows for busses to access passengers waiting at a bus stop on the sidewalk. This results in a temporary interruption in the separation between bus and bicycle traffic. Cyclists riding behind the bus when it pulls over to the bus stop can either pass the bus by moving into the roadway or wait behind the bus. A problematic situation can arise when a bus driver pulls out of the bus stop and into the roadway while a cyclist is carrying out an overtaking maneuver. Kaparias et al. (2021) noted that cyclists ride significantly faster when there is a bus stop present. The authors suggested that this is due to the increased width of the road at bus stops. I propose, however, this might be due to the need to accelerate to merge into motor vehicle traffic to pass stopped busses.

c. **Shared bus-cycling facility**: In some places, busses and cyclists share a designated lane for only these two modes. De Ceunynck et al. (2017) found close interactions to be common on these types of lanes and observed many instances in which a bus passed with a lateral clearance of less than 1 m or followed a cyclist at a headway less than 2 s.

Figure 2: Examples of solutions for combining cycling infrastructure with a bus stop

Because crashes with motor vehicles, trucks, and busses have more severe consequences in terms of injury and fatalities, it is likely that bus stops combined with on-road cycling facilities pose a greater risk to cyclists. Further research is needed to examine different bus stop/cycling infrastructure configurations and compare the number and severity of conflicts and crashes at each type.

Motorists

Motorists and cyclists must interact on road segments without marked cycling infrastructure (mixed traffic) and on segments with on-road infrastructures, such as painted bicycle lanes or other markings to indicate the presence of bicycle traffic. Mainly, these interactions are characterized by a faster-moving motorist approaching, following, and/or passing a slower-moving cyclist. Researchers have largely focused on the behavior of motorists, likely because they have a better overview and more control in the interaction. However, if a rear-end or sideswipe crash takes place, the cyclist is likely to bear the brunt of the impacts. Indeed, motorists passing cyclists with an insufficient lateral distance is a crucial safety problem on road segments (Johnson et al., 2010; Pai, 2011; Stone and Broughton, 2003). Even when passes with a low lateral distance do not result in a collision or critical interaction, the comfort and subjective safety of the cyclist is decreased (Beck et al., 2021), which can lead to reduced bicycle use in the long term (Parkin et al., 2007) and a decrease in the uptake of cycling (Aldred and Crosweller, 2015).

Many jurisdictions around the world have introduced minimum lateral clearance distances to reduce rear-end and sideswipe crashes between cyclists and passing motorists. For example, motorists are required to maintain a minimum passing distance of 1 m in Australia and 1.5 m in Germany. Several US American States stipulate a minimum passing distance of 3 ft. (~0.9 m) or 5 ft. (~1.5 m). Despite these measures, issues with insufficient lateral passing distance persist. Non-compliance rates found in the literature range between 2 % and 16 % (Debnath et al., 2018; Love et al., 2012; Oh et al., 2019). Although this range of compliance rates can likely be explained in part by the size of the required passing distance, not enough research is available to systematically compare this effect. Additional factors, such as characteristics of the roadway, the traffic culture, and the modal split likely affect passing distances as well. The availability of open sensor systems for detecting passing distances, such as 1M+ (Henao et al., 2021) will enable the widespread analysis of lateral passing distances.

The infrastructure design has been found to have an important impact on the lateral positioning of both motorists and cyclists during a passing maneuver. For example, close passes are observed more often on curved road segments as opposed to straight sections (Debnath et al., 2018). As would be expected, narrow traffic lanes lead to closer passing behavior (Debnath et al., 2018; Nolan et al., 2021). The presence of a marked bicycle lane has multiple positive effects. Firstly, the lateral position of the cyclist in relation to parked cars is increased (Duthie et al., 2011), which reduces the likelihood of a dooring incident and indicates a feeling of comfort. Secondly, the lateral distance between a cyclist and a passing motorist increases in the presence of a bicycle lane (Chuang et al., 2013; Love et al., 2012; Nolan et al., 2021; Oh et al., 2019). Finally, the subjective safety of cyclists using a bicycle lane is higher during passing events (Beck et al., 2021). The presence of protected bicycle lanes has been found to greatly increase the lateral passing distance in comparison to painted bicycle lanes (Nolan et al., 2021). Other markings that indicate the presence of bicycle traffic, such as 'sharrows' (painted pictograms on the pavement indicating the presence of cyclists) have not been found to increase the lateral passing distance between motorists and cyclists or to encourage cyclists to ride in a safer position away from parked cars (Oh et al., 2019).

The characteristics of the motorist and cyclist play a role in the lateral passing distance and the perceived danger of an interaction. Passes carried out by trucks and other large vehicles are perceived as being particularly dangerous (Aldred, 2016; Aldred and Crosweller, 2015; Beck et al., 2021), push cyclists to the side of the road (De Ceunynck et al., 2017), and result in less lateral stability of the cyclist (Chuang et al., 2013). The lateral position of the cyclist is an important determinant of the lateral spacing granted by the motorist; for each foot of additional lateral space of the cyclist from the curb or parked vehicles, a motorist moves 0.5 feet further to the center of the road (Duthie et al., 2011). As a result, the lateral clearance distance between motorists and cyclists decreases when cyclists ride further into the vehicle lane. Researchers have found that motorists tend to grant wider lateral passing distances to female cyclists (or those who appear to be female) (Chuang et al., 2013; Walker, 2007).

There has been significantly less attention from researchers about the actions and reactions of cyclists in situations with a passing motorist. Duthie et al. (2011) estimated that cyclists deviate about 0.2 m from their intended path when being passed by a motor vehicle. Chuang et al. (2013) found that the steering angle, the speed, and the variation in speed of the cyclist affected the passing behavior of the motorist. In terms of safety-critical behavior, Johnson et al. (2010) found that cyclists rode in a safe/legal manner before a crash, near miss, or another type of incident on a road segment in 88,9 % of the cases.

Although passing maneuvers are the most common and (therefore) problematic type of interaction on road segments, another problem on multiple lane roads is the tendency of motorists to make a sudden lane change maneuver and fail to notice or react to cyclists (Johnson et al., 2010).

Other cyclists

Road segments are characterized by a direction of travel and can be either one-way or bi-directional. As such, interactions between cyclists can be categorized as following, passing, or meeting events. A following event is a situation in which a faster-moving cyclist approaches a slower cyclist traveling in the same direction and adjusts his or her speed to follow the slower cyclist. During a passing event, the faster moving cyclist passes a slower cyclist by changing their velocity (speed and or direction). A meeting event is defined as a situation in which two cyclists traveling in opposite directions approach each other and adjust their velocity to maneuver around one another.

A passing event is characterized by the following three parameters:

- **Speed:** Khan & Raksuntorn (2001) found an average speed difference between passing and passed cyclists of 2.6 m/s, which was found to remain relatively constant throughout the maneuver. A minimum speed difference of 1.5 m/s was noted. If the difference dropped below this threshold, the passing cyclist was found to increase his or her speed. In contrast, Botma & Papendrecht (1991) found passing cyclists maintain a constant speed while carrying out a passing maneuver. Falkenberg et al. (2003) found that the passing cyclist usually does not have to reduce his or her speed in reaction to the cyclist who is to be passed.

- **Length/duration of passing event:** There is a weak indication that the length of the passing maneuver increases with the width of the infrastructure. Passing maneuver lengths of 57 m (11.0 s) and 24 m (4.5 s) were found for 2.4 m and 1.8 m wide separated bicycle paths (Botma and Papendrecht, 1991). Longer passing maneuvers with an average of 91.4 m were observed on a 3 m wide bicycle path (Khan and Raksuntorn, 2001).

- **Lateral spacing:** A German study found the average, minimum and maximum lateral spacing between cyclists to be 0.60 m, 0.20 m, and > 1.00 m, respectively (Falkenberg et al., 2003). A US American study estimated larger values for the average, the minimum, and maximum lateral spacing of 1.78 m, 1.35 m, and 2.36 m, respectively (Khan and Raksuntorn, 2001). As well as the type and width of the facility, other conditions, such as whether it was in an urban or rural region, may influence lateral spacing.

Meeting events were examined in a controlled experiment in the Netherlands (Yuan et al., 2018). Findings show that both cyclists in an interaction deviate from their intended lateral position and that women deviate more from their desired path than men do. The observed cyclists began deviating from their intended paths when they were about 30 m apart and the maximum lateral deviation is between about 0.5 m and 0.8 m. Khan & Raksuntorn (2001) measured an average lateral spacing at the moment that two cyclists meet of 1.95 m on a 3 m wide separated bicycle path.

The number of passing and meeting events influences the Level of Service (LOS) for cyclists. Botma (1995) suggested using the number of hindrance events, which are passing, meeting or combined passing, and meeting events, as an indicator of the LOS for cyclists on separated facilities. Each hindrance event is presumed to force a cyclist to adjust their speed or path, which in turn decreases efficiency, comfort, and possibly safety. This method has been adopted in a modified form in both the American Highway Capacity Manual (National Research Council, 2010, 2000) and the German "*Handbuch für die Bemessung von Straßenverkehrsanlagen*" (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2015). Although the number of passing and meeting events is widely used in determining LOS on bicycle facilities, it has been noted that they are relatively difficult to measure in the field (Gould and Karner, 2010).

Researchers have placed more attention on the flow of bicycle traffic in the last couple of years. Within the European research project *allegro* (unraveling slow mode traveling and traffic) at the TU Delft, experiments were carried out to study how cyclists interact with each other and the implications of these interactions on the flow of bicycle traffic. Hoogendoorn & Daamen (2016) introduced a model for bicycle traffic headway that takes into account the lateral flexibility of cyclists and classifies headways as constrained (a cyclist is following another cyclist and cannot or does not want to overtake) or unconstrained. They estimate that all cyclists move freely when headways greater than 4 s are present. Wierbos et al. (2019) examined the positioning of cyclists on facilities with varying widths and found support for the theory that cyclists divide available space into sub-lanes. Values for the capacity of cycling infrastructure of various widths are derived. Still, the mechanisms that underpin the behavior of cyclists in areas with large volumes of bicycle traffic and the variations due to type of infrastructure, country, culture, type of bicycle, and characteristics of the cyclists themselves require more attention.

Interactions at intersections

While it is possible to separate bicycle, motor vehicle, and pedestrian traffic on road segments, road users must come together and interact with one another at at-grade intersections. Throughout the European Union, 36 % of cyclist fatalities occur at intersections, which is extremely high in comparison to other modes. Interestingly, in the European countries with high modal splits of bicycle traffic, cyclist fatalities are more likely to take place at intersections rather than on road segments (European Commission, 2020a). In this section, two topics are discussed, the gap acceptance of cyclists and other road users interacting with cyclists and critical interactions with heavy-duty vehicles. Please note that all turning directions mentioned in this chapter are based on right-hand traffic.

At signalized intersections, priority is granted to a large degree by the traffic signal. Conflicting streams, such as crossing and left-turning road users, are often served in the same signal phase and road users must yield to one another based on traffic laws. At non-signalized intersections, road users must determine and grant the right of way for each interaction (again based on traffic laws). Gaps are the distance in space or time between two road users following each other or to the nearest approaching road user in an opposing traffic stream. Gap acceptance describes the minimum gap size utilized by road users to cross an opposing stream and has an enormous effect on traffic flow and cyclist safety at intersections.

A critical safety issue for cyclists is interactions with heavy-duty vehicles. Although interactions with heavy-duty vehicles are important on road segments as well, this topic is included in this section because of the acute problem with interactions between cyclists riding straight across the intersection and heavy-duty vehicles turning right.

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Gap acceptance

Gap acceptance plays an important role in the interaction of conflicting traffic streams at intersections. The most common examples of gap acceptance are left-turning vehicles or cyclists serviced in the same phase as vehicles or cyclists moving straight across the intersection in the opposite direction. Another example is road users turning left or right that must pass through a stream of pedestrians or cyclists crossing adjacently in the same phase. In many places, the turning vehicle or cyclist must wait for a large enough gap in the prioritized stream. Of course, there are different regulations for interactions in different countries.

The only factor found to affect the gap acceptance of cyclists is the type of stop they perform. Opiela et al. (1980) studied the gap acceptance of 260 cyclists as they crossed two lanes of one-way motor vehicle traffic. They found gap acceptance to be affected by the type of stop, with cyclists who came to a rolling stop accepting much shorter gaps compared to those who came to a complete stop. The observed gap acceptance data was found to follow a logarithmic distribution. The critical gap, which represents the intersection between the gap acceptance and gap rejection, was found to be 3.2 s. Hoogendoorn & Daamen (2016) estimated a so-called empty space distribution, which can be used to determine the number of gaps that can be used by crossing traffic.

Gap acceptance across the driving population regulates the overall traffic efficiency at intersections. Many researchers have investigated traffic volumes and the resulting delay at intersections. Allen et al. (1998) studied the relationship between the bicycle traffic volume on a given intersection approach and the percentage of the green phase in which the conflict area for left and right turning vehicles is blocked by cyclists. They concluded that there are a sufficient number of large gaps and therefore very little impact on traffic flow when the volume of bicycle traffic is less than 60 cyclists/hour. A linear equation was developed to predict the proportion of green time during which the conflict zone is occupied based on the volume of bicycle traffic. Extrapolation was used to predict that a full blockage of the conflict zone occurs at 2646 cyclists/hour green. Grigoropoulos et al. (2022) found in Germany that a flow of 600 cyclists/hour at an intersection approach reduces the capacity of right-turning motor vehicle traffic at the same approach by approximately 50 % and of left-turning vehicles on the opposite approach by nearly 65 %.

Gap acceptance plays a central role in the safety of cyclists at intersections. A major safety concern at signalized intersections involves vehicles turning right in the same signal phase as cyclists traveling straight across the intersection, which are often positioned to the right of the turning vehicle traffic. This leads to situations in which drivers do not see cyclists (look-but-failed-to-see-error) or accept gaps in bicycle traffic that are not large enough.

Heavy-duty vehicles

The most dangerous interactions for cyclists in urban areas are those with heavy-duty vehicles. In Europe, 13 % of cyclist fatalities resulting from a crash with another road user followed an impact with a truck. Several countries with relatively high modal splits of cycling, including Denmark and Switzerland, have shares of cyclist fatalities from truck-cyclist crashes above 20 % of all cyclist collision fatalities. Part of the problem is that when cyclist-heavy duty vehicle crashes occur, the consequences for the cyclist are likely to be more severe than for collisions with any other type of road user (Kim et al., 2007; Manson et al., 2013). In addition, as a result of megatrends such as urbanization and increased online shopping, the number of heavy-duty vehicles in urban areas is growing and researchers have noted a troubling lack in developments concerning city logistics (Dablanc, 2007). These factors together suggest that the bicycle-truck problem in urban areas will likely become worse in the future.

Pokorny & Pitera (2019) provide a summary of 43 studies relating to crashes and conflicts between cyclists and heavy-duty vehicles. They report that the most serious risk factor for cyclist-truck collisions is limited visibility; mainly the problematic blind spots beside, in front, to the sides, and behind the truck in which drivers are not able to see cyclists, pedestrians, and any other road users. Other problems with blind spots, such as lack of awareness about the problem, cyclists' incorrectly presuming that a truck driver can see them, improper adjustment of mirrors by truck drivers, leading to larger blind spots, and a lack of proper truck equipment are found to be risk factors for cyclist-heavy duty vehicle collisions.

Large trucks and rigid trucks, particularly those linked with construction activities, are particularly dangerous for cyclists due to their large blind spots, large turning radii, and limited maneuverability (Niewoehner and Berg, 2005). For this reason, and because large trucks are known to cause congestion in urban areas, many cities are implementing policies to replace large trucks with many smaller trucks (Taniguchi, 2014). However, trucks are not only dangerous for cyclists when they are driving but also when they are parked. The number of smaller-sized delivery vehicles carrying the packages and parcels ordered online is growing at a rapid rate and in many cases, there is insufficient temporary parking available for these trucks. Hence, many truck drivers park on sidewalks and bicycle lanes out of necessity and temporarily block these facilities for their intended users. Based on observations of cyclists' interactions in Munich, Germany, Silva et al. (2020) reported that cyclists often break traffic laws by moving into an adjacent vehicle lane to pass a delivery vehicle (even though these vehicles only block the lane for a short period). This behavior puts cyclists at risk for dangerous interactions with passing motorists (see the previous section about motorists).

Shared Space

In the previous two sections, I investigated infrastructure designs with a large degree of separation between active and motorized modes of transport. This is a common approach to ensure high traveling speeds for motor vehicles while ensuring safe conditions for pedestrians and cyclists. The concept of shared space is different in that there is no physical segregation between the modes of transport and the speed of faster road users is reduced to ensure safe interactions for all. Because of the lack of physical separation, there is an increased need for interaction and cooperation. As a result, shared spaces are characterized by more conflicts, greater attentiveness of all road users, and smaller differences in traveling speed between modes (Kaparias et al., 2013). Researchers in Austria have found the variance in observed speeds per road user is smaller in shared space than on other types of infrastructure because road users do not need to start and stop as often (Schönauer et al., 2012). However, although injuries are rare, physical contact between road users is common in shared spaces and conflicts are a cause for concern of both pedestrians and cyclists (Gkekas et al., 2020).

The density of the shared space has a large impact on the behavior, interaction, and comfort of road users. As expected, cyclists' traveling speeds are lower (Alsaleh et al., 2020; Beitel et al., 2018; Essa et al., 2018) and the number of conflicts between cyclists and pedestrians is higher (Beitel et al., 2018) in shared spaces with high pedestrian densities. The higher density also leads to more close interactions, which lowers the perceived safety of pedestrians (Kiyota et al., 2000). Subjectively, cyclists and pedestrians see high density and inattentiveness as risk factors for conflicts and crashes

(Gkekas et al., 2020). As discussed in previous sections, it appears that pedestrians are more likely to adjust their behavior and yield to a cyclist than the other way around in a shared space (Che et al., 2021).

No studies were found in the review that investigate the behavior and interactions in shared spaces with motorized vehicles.

Discussion

Interactions between cyclists and other road users are a normal part of moving through an environment on a bicycle and are not in themselves problematic. The opposite is true; the lack of a hard shell and a slower traveling speed allows cyclists the opportunity to experience and interact with the surrounding environment and with other people using the road. So where does the problem lie? A major issue is the failure to perceive and then predict the development of a potential problem.

Based on an in-depth analysis of cyclist-motorist crashes in Sweden, Räsänen & Summala (1998) reported two common mechanisms in collisions. First, road users fail to detect or see an interacting cyclist or motorist and a potentially critical situation. They found that in 37 % of studied crashes, neither road user perceived the danger before the crash occurred. Similarly, an Australian review reported that in over 60 % of collisions, a major contributing factor was that neither the cyclist nor the driver saw the other road user before the collision happened (Australian Transport Safety Bureau, 2006). A common problem is that people tend to thoroughly check for other road users in areas where they are expected and neglect, or quickly scan, spaces where they are not. Many cyclist-motorist crashes happen at non-signalized intersections when a vehicle turning right crashes into a cyclist that approaches from their right-hand side (Gerstenberger, 2015; Herslund and Jørgensen, 2003; Räsänen and Summala, 1998; Summala et al., 1996). In this situation, the motorist expects interacting road users to approach from the left-hand side and therefore visually searches this area more thoroughly than the space on the right-hand side (Summala et al., 1996). Even if they do scan the right side, they are more prone to a "look-but-failed-to-see-error" because the cyclist does not fit into the driver's fixed search strategy (Herslund and Jørgensen, 2003).

How can urban infrastructure planners and traffic engineers address this issue? They must design and build infrastructure that is uniform, direct, and easy to understand for all road users. This will support the positioning of all persons in spaces where they are expected by other road users. It is also important to ensure high visibility for cyclists, motorists, and pedestrians to physically be able to see one another. Finally, technology may assist motorists in detecting other road users and upcoming interactions before they become critical. A key example of this is drivers' assistance systems that detect cyclists and pedestrians in the blind spots of large trucks and warn the truck driver.

The second common failure according to Räsänen & Summala (1998) is the incorrect prediction of the upcoming behavior of other road users. People express their intention and upcoming manoeuvers with one another using implicit and explicit communication strategies. Implicit communication strategies convey messages to other road users without using direct signals. Examples include changing speed or direction or looking in a certain direction. Explicit communication on the other hand involves direct signals such as hand waving, honking a horn, or ringing a bell on a bicycle. Successful communication forms the basis of all normal encounters and is essential in resolving conflicts (Abendroth et al., 2019).

What can be done to address the failure to predict the behavior of other road users? Again, clear and easily understandable infrastructure is the key. Rules and regulations that ensure predictable behavior and the enforcement of these rules may help create a predictable road environment. However, a much more effective measure may be a simple reduction in speed limits and the introduction of traffic calming measures. When traveling at slower speeds, road users have more time to correct misinterpretations of upcoming behaviors. And if a collision does happen, the consequences are less severe at low speeds in comparison to higher speeds. Again, technology may offer assistance in predicting the behavior of other road users. Developers of automated driving systems are very keen to create systems that can implicitly and explicitly communicate with human cyclists, pedestrians, and motorists, predict behaviors and react in ways that are understandable to others.

In situations in which a cyclist detects and perceives an upcoming risk, correctly predicts the behavior of the interacting partner, and communicates their intention, a final potential problem is the failure to properly adjust their operational behavior (e.g. speed and direction). This is particularly relevant for cyclists in comparison to users of other modes because riding a bicycle requires physical skill, balance, and strength in a dimension different from walking or sitting and driving a motor vehicle. If a cyclist loses operational control during an interaction, he or she is at risk of a fall, which can have serious consequences as well. This factor is particularly important for elderly cyclists and children.

What can be done to help cyclists adjust their speed and direction and react to critical situations without losing control of their bicycles? Once again technology may be able to assist. For example, researchers at the TU Delft are in the process of developing assistance systems that help cyclists stay upright when riding at slow speeds (TU Delft, 2019).

Bicycle traffic is becoming increasingly diverse. Pedelecs and other electrically supported bicycles, pod bicycles, cargo bicycles, e-scooters, and other forms of micromobility are growing in popularity. Each of these new forms of mobility is distinct in terms of driving dynamics and use. The interactions between users of these new modes and other road users may be similar to those of cyclists, but not identical. As these new modes become more commonplace, researchers will have the opportunity to examine interactions at all levels of the Safety Pyramid.

Conclusion

The topic explored in this chapter is very broad. I categorized cyclists' interactions according to the infrastructure (road segment, intersection, or shared space) and by the type of interaction (cyclist, motorist, heavy-duty vehicle, bus, or pedestrian). Interaction constellations that are known to lead to conflicts or crashes with potentially severe outcomes for cyclists, such as motorists overtaking cyclists on roadways, are the focus of the vast majority of the papers identified in this review. Fewer papers were found that examine normal interactions, or encounters according to the Safety Pyramid, and most of these were undertaken with the goal of modeling bicycle traffic for application in microscopic traffic simulations. Another aspect that has not been thoroughly covered in the literature is the subjective experience of interacting, particularly with consideration of the benefits interactions bring to the cycling experience.

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