A Taxonomy of Countermeasures for Cyclist – Vehicle Crashes

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Abstract

As downtown areas continue to grow, residents are encouraged to use alternative modes of transportation, inducing cycling. Therefore, cycling is experiencing a growth, mainly in urban areas. Although cycling offers significant health, cost, and time benefits, cyclist safety within motor vehicle traffic appears to be deteriorating. Traffic injuries and fatalities have been declining in general, but the number of cyclists who die or are severely injured in crashes has been increasing. This increase in cyclist injuries/fatalities is likely due to the existing vehicle, infrastructure, and policy designs failing to facilitate the increase in cycling volume. We present a review of countermeasures suggested or implemented to improve cycling safety and propose a taxonomy dividing these countermeasures into three design categories: gear/vehicle, infrastructure, and policy. The scope was restricted to cyclist-driver interactions since bicycle-bicycle and bicycle-pedestrian collisions tend to be less severe. Based on the somewhat limited evidence reported in the literature, it appears that infrastructure design solutions are the most effective. We present an overview of the available evidence and also highlight countermeasures that require further evaluation.

Résumé

Comme le centre-ville continue à s'élargir, les habitant sont encouragés à utiliser des modes de transport alternatifs, induisant le cyclisme. En conséquence, ce dernier connaît une croissance, principalement dans les zones urbaines. Bien que le cyclisme offre des avantages considérables en termes de santé, de coût et de temps, la sécurité des cyclistes dans la circulation automobile semble se détériorer. Les accidents de la route et les décès ont généralement diminué, mais le nombre de cyclistes décédés ou gravement blessés dans des accidents cycliste- conducteur a augmenté. Cette augmentation du nombre de blessures et de décès chez les cyclistes est probablement due à l'échec des conceptions existantes des véhicules, des infrastructures de routes et de la politique routière mise en place pour augmenter le volume de cyclisme. Nous présentons un examen des contre-mesures suggérées ou mises en œuvre pour améliorer la sécurité des cyclistes et proposons une taxonomie divisant ces contre-mesures en trois catégories de conception: engins / véhicules, infrastructures de routes et politiques routières. Le champ d'application était limité aux interactions cycliste-conducteur, car les collisions entre cyclistes et cyclistes-piétons ont tendance à être moins graves. Sur la base des preuves limitées rapportées dans la littérature, il apparaît que les solutions de conception d'infrastructures sont les plus efficaces. Nous présentons un aperçu des preuves disponibles et soulignons également les mesures à prendre nécessitant une évaluation plus poussée.

BACKGROUND

The overwhelming majority of people living in large cities with busy downtown areas, such as Toronto, Ontario, do not prefer to drive due to traffic congestion and limited parking resources [1]. As downtown areas continue to grow, residents are encouraged to walk, cycle, and take transit [2]. Overall, cycling is experiencing a growth in urban areas [2]. For instance, from 2001 to 2006, the percentage of Toronto commuters who chose cycling over other forms of transportation went from 1.3 to 1.7%, an increase of 31% [3].

Despite the benefits of cycling, cycling safety within motor vehicle traffic appears to be deteriorating. Given the minimal level of protection cyclists have, they are more likely to suffer major injuries or fatalities in a crash compared to vehicle occupants [4]. Although the total number of traffic fatalities have been declining in the past decade, an increase in the rate of cyclist fatalities has been observed: Cyclist fatalities accounted for 2.2% (840) of the total 37,461 U.S. traffic fatalities recorded in 2016, compared to 1.7% (701) of the total 41,259 fatalities recorded in 2007 [5]. Similarly, from 2005 to 2014, the percentage of cyclists killed or seriously injured in the UK among all fatalities and serious injuries has doubled from 7% (2,360) to 14% (3,514) despite the decline in the total number of traffic fatalities and major injuries from 32,155 to 24,582 [6].

The annual mileage traveled is significantly less for bicycles than for motor vehicles. For example, the average annual distance traveled per person in the UK in 2014 was found to be 90 km for cycling and 5,272 km for driving [6]. Controlling for mileage exposure, it was found that in the Netherlands there are about 5.5 times more traffic fatalities per kilometer traveled by bicycle than by car [7]. Controlling for trip exposure (i.e., number of trips taken), U.S. cyclists have been found to be 2.3 times more likely to die in a crash compared to a vehicle occupant [8]. A further look at severe cyclist crashes reveals that the majority of them take place in urban areas: 71% percent of U.S. cyclist fatalities in 2016 occurred in urban settings [5]; this rate was 75% for the UK [9]. Within large cities, such as Toronto, most cyclist fatalities appear to occur in the downtown core, which can in part be explained by the growing demand for cycling in busy city cores: 69% of cyclist fatalities recorded in Toronto in 2010 occurred in downtown areas [3].

Although crash data indicate an increase in the rate of cyclist fatalities and serious injuries, the data collected may not fully reflect the extent of the problem. Underreporting of cyclist crashes to police has been shown to be a worldwide problem [10]. Even in a bike-friendly country such as the Netherlands, police-report data showed a 26% decrease in cyclist serious injuries from 2000 to 2009, whereas hospital records indicated a 35% increase [11]. The disparity between reality and police records is likely to be larger for non-severe cyclist crashes [4]. In a survey of 7,015 active cyclists across 17 countries, 37.6% of the cyclists who self-reported to having been admitted to hospital after a crash said that they reported the crash to the police; the police-reporting rate was only 3.9% for crashes with no medical attention [10].

Overall, it is clear that cycling safety is becoming a greater concern as cities grow around the world. Efforts are underway around the world to eliminate cyclist fatalities and serious injuries through Vision Zero programs. The first Vision Zero act was established in Sweden in 1997 to entirely eliminate serious injuries and fatalities that occur on the roads [12]. Since then, Vision

Zero has been implemented in other European countries and more recently in Canada [13] and in the U.S. [14]. These programs take on a comprehensive approach to enhance road safety, targeting policy, infrastructure, and vehicles [12]. With this perspective, it is important to systematically identify ways to prevent or mitigate cyclist crashes, which may be due to several factors including improper road user behaviours, poor infrastructure design, and lack of policy and enforcement [15].

PROPOSED TAXONOMY

In this paper, we propose a taxonomy to systematically categorize design interventions on vehicle/gear, infrastructure, and policy that target cyclist-driver interactions and related crash outcomes. The scope was restricted to cyclist-driver interactions for this first effort to create a taxonomy since bicycle-bicycle and bicycle-pedestrian collisions tend to be less severe. For example, in the U.S. between 2001 and 2004, cyclists who were injured in a collision with a motor vehicle were 2.6 times more likely to warrant hospitalization or transfer for specialized medical care compared to cyclists who were injured in other collision types [16]. We also provide an overview of the available evidence regarding countermeasure effectiveness and also highlight potential interventions that require further evaluation.

ROAD USER	Vehicle/Gear	Infrastructure	Policy Design
DRIVER	Maintenance e.g., quality of windshield wipers Assistive Car Technology e.g., blind spot detection	Maintenance e.g., adequate quality of road surface Control Elements e.g., dedicated bicycle signals Road Layout e.g., dedicated bicycle lanes	Education & Training e.g., right-of-way knowledge Regulatory Laws e.g., no right-turn-on-red Enforcement e.g., fines for motor vehicle intrusion to bicycle facilities
CYCLIST	Maintenance e.g., tire pressure Detection Enhancing Gear e.g., reflective vest, bell Assistive Bicycle Gear e.g., rear-view mirror on bicycle Protective Gear e.g., helmet		Education & Training e.g., avoiding wearing black clothing Regulatory Laws e.g., license plates for bicycles Enforcement e.g., detection system for violations

Table 1. Taxonomy of countermeasure design for cycling safety (an example provided for each countermeasure)

Vehicle/gear

Crash risk and severity can be reduced through the introduction and adoption of enhanced protective and assistive technologies, as well as the adoption of regular maintenance schedules.

Proper ***maintenance of vehicles*** (cars and bicycles) is required to ensure that both cyclist and driver actions are carried out as intended. For example, proper tire type and pressure translate to efficient braking [17] and working windshield wipers and signals prevent delays in visual detection [18].

Assistive car technologies can help drivers in detecting cyclists and reacting in complex situations. For example, blind spot detection technology has been implemented within cars with about 78% precision rate for vehicle and motorcycle detection [19], but needs further development for detecting cyclists [20]. More comprehensive detection systems have been proposed with the system presenting peripheral cues on a head-up display informing the driver to switch their attention to areas/objects of importance [21]. A recent instrumented vehicle study conducted in downtown Toronto found that half of the drivers who participated failed to allocate proper attention to cyclists at least during one of two intersection maneuvers they performed [22]. Therefore, there is a need to alert drivers about cyclists in their vicinity. The alerting can be through the visual modality as is the case for head-up displays, but also through other modalities such as through auditory or tactile warnings. Auditory and tactile warnings are omnidirectional [23] and can alert drivers of the presence of a cyclist even when the driver's visual attention is not directed towards the visual display. Assistive technologies can go one step further from aiding the driver in cyclist detection to also assisting them in vehicle control, for example, by applying the brakes if the driver fails to react in a timely manner. There are such systems implemented in current production vehicles; Tesla Model S provides automatic braking if an imminent crash is anticipated [24]. These types of systems might be particularly useful for cars that have wider A-pillars that can block the view of the driver. In general, the reliability of assistive car technologies need to be improved, and various efforts are underway to develop smarter vehicle and infrastructure systems (e.g., roadside radars and cameras understanding cyclist intentions and communicating this information to vehicles, direct communication between vehicles so that the car is aware of the bicycle trajectory). Although there has been a substantial upsurge in intelligent transport system research in the past decade, most of these systems are not yet ready for implementation. A major concern is overreliance of drivers/cyclists on such technologies that are less than perfect as the primary agent to detect and react to roadway conflicts.

Between 2010 and 2015, 12.1% of U.S. cyclists were fatally struck as they were not visible [14]. Therefore, cyclist visibility plays a large role in their detection and can be enhanced by adopting ***detection enhancing gear***, such as reflective vests, flashing lights, and bells. Wearing fluorescent and reflective vests [25] in addition to light clothing, installing pedal reflectors and flashing or steady lights [11] have been recommended to increase visibility. Daytime usage of bicycle lights has been correlated with a 30% reduction in self-reported crashes [26]. The importance of reflective clothing in low lighting appears to be recognized more by drivers (95% of surveyed drivers) than by cyclists (72% of surveyed cyclists) [25]. Therefore, this type of countermeasure may need to be supported through policy and education.

Cycling performance can be improved through ***assistive bicycle gear***, such as the installation of a rear-view mirror on the bicycle to extend the field of view of the cyclist, and through gloves and sunglasses to improve grip and to protect vision from the sun and debris.

Protective gear worn by cyclists, such as helmet and knee/elbow pads, can reduce the impact of a crash on the cyclist. About 45% of the U.S. cyclists who were hospitalized due to a collision with a motor vehicle, had a head/neck injury, followed by 27% who had an injury of lower extremities. Among those with a head injury, 85% were diagnosed with a concussion [16]. Therefore, head is an important body part to protect as a cyclist. Helmet wearers are significantly less likely to experience fatality (odds ratio, OR: 0.27) and head injury (OR: 0.40) [27]. Wearing a helmet is generally highly recommended by government agencies but is not compulsory in many jurisdictions around the world [28].

Infrastructure

Proper design and maintenance of infrastructure can also significantly mitigate driver-cyclist crashes.

Proper ***maintenance*** *of* road surface, markings, control elements, along with roadside furniture (e.g., trees limiting sight distance) is essential for road safety. Maintenance of bike paths is also critical since the accumulation of any obstacle on the path (e.g., debris, snow) or poor pavement quality is deterrent to cycling [2] and can force cyclists to ride closer to vehicles. The elimination of highway defects from four districts in the UK was forecasted to increase proportion of cycling to work by 1.3 to 12.9% [29]. Further, obstacles on cyclists' path can create distractions for cyclists. For example, a survey of 1064 cyclists from various countries found that about 84% of cyclists consider obstacles on their path as distractions [30]. Adequate road lighting should also be ensured; police reports between 1997 and 2002 from the U.S. revealed that cyclist fatality probability is higher by 111% on dark, unlit roads compared to those with streetlights or under daylight conditions [31].

Motor vehicle and bicycle traffic are informed and directed through ***control elements***. Clear, legible and salient road furniture tailored to particular circumstances (e.g., maneuvering) and driver groups (e.g., unfamiliar drivers) can ease the task of negotiating the road environment [32]. Implementing signal countdown timers (i.e., showing the remaining red and green phases) [33] and a flashing green phase prior to the amber phase [34] have both been found to reduce red-light running incidents. Similarly, a flashing amber beacon mounted at stop-controlled intersections can alert drivers in advance about the presence of an upcoming stop sign [35]. This intervention appears to be more beneficial for rural sites [35], which encompass long stretches between intersections and thus drivers are more likely to miss an intersection [36]. Advanced-stop lines for cars (a.k.a., green bike box project) can make cyclists more visible and facilitate safer left-turn areas for them. Upon installation of advanced-stop lines in Portland, U.S., drivers were found to exhibit better yielding behaviours to cyclists, and the overall number of conflicts between cars and bicycles reduced by 30% [37]. Further, dedicated bicycle signals at intersections can separate cyclists from vehicle traffic in time. Over a 35-month span after signal modification, no vehicle-cyclist crashes were reported in Davis, California, where there were 12 incidents in the preceding 35-month time period [38].

In terms of the ***road layout***, separating cyclists from motor vehicle traffic to various extents is the most common intervention suggestion, since cycling mixed with vehicle traffic is less preferred [39]. Robbins and Chapman [40] argue that crashes are more likely to be linked to drivers' attention failures towards cyclists when cyclists and vehicles share the same road. Further, the presence of motor vehicle traffic can be a source of distraction for cyclists, leading to attentional failures on their part. For example, the survey from 1064 cyclists reported earlier also found that about 84% of cyclists considered other road users to be sources of distraction [30]. The separation between the two modes of transportation can be introduced by pavement coloring (e.g., a solid white line), physical barriers (e.g., bollards, roadside planters, on-street parking lane), raised median, and cycle tracks (i.e., exclusive two-way bike tracks) [2]. On-street parking lanes have also been implemented between motor vehicle and bicycle traffic as they can act as a buffer between the two modes of transport [41]. However, this approach can introduce unanticipated hazards for cyclists such as dooring from the passenger side [13] or blocking the drivers' view of cyclists until the two traffic modes mix again at intersections [22]. In a meta-analysis study, [41] found that cycle tracks are the most effective road layout strategy for preventing injury among the ones that were evaluated (i.e., bicycle boulevard, bike box, bike lanes, cycle track, multi-use path, neighborhood traffic circle, raised bicycle crossing, removal of on-street parking, roundabout bike lane, roundabout general, roundabout mixed traffic, roundabout multi lane, roundabout separated bike facility, street lighting). The risk ratio compared to a similar road without any cycle tracks was estimated to be around 0.12. Removal of on-street parking was also found to be effective, with a risk ratio of around 0.61. Cyclists also appear to perceive cycle tracks as the safest and prefer to use them; survey respondents from Toronto and Vancouver, Canada reported that they feel safest when riding on cycle tracks and prefer them highly [42].

Cycle tracks are effective in reducing injury risk, but their effectiveness may degrade when they are designed to merge with motor vehicle traffic at intersections [43]. In general, it is important to provide undisrupted pathways for cyclists not only throughout midblocks, but also through intersections, which can be facilitated through delineated markings, cyclist undercrossing, overcrossing, floating bus stop (i.e., directing cyclist traffic around bus stop zone), or jug-handle left turns for cyclists [44]. Although a report on crashes on 148 roundabouts in Belgium [45] suggested the removal of roundabouts as they had been found to increase injury risk for cyclists by 27%, a recent before-after study from Denmark argued that single-lane roundabouts with a dedicated bike path are safer than mixed conventional intersections, as they allow cyclists to operate separately from motor vehicle traffic [46]. In addition, a more comprehensive approach, such as a road diet (i.e., a lane reduction or road channelization) can introduce or add bike lanes to an area, eliminate on-street parking lanes that may create hazards to cyclists (e.g., dooring), and even reallocate traffic to create vehicle-free streets [2]. A road diet treatment in three U.S. states indicated a 29% reduction in the total number of collisions as well as a reduction in speed. With two through lanes and a center lane for turning, cars were restricted by the speed of the vehicles ahead [47]. In addition, removal or separation of streetcar and railroad tracks from traffic is advised [48] since these tracks impede riding activity, and significantly increase the cyclist injury risk by threefold [42].

Policy

Policy design offers guidance on the development, implementation, and adoption of the vehicle/gear and infrastructure strategies that have been discussed above.

Education and training countermeasures can range from the redesign of driver handbooks to marketing campaigns to driver/cyclist training programs. For example, driver handbooks can be updated to clearly convey right-of-way information related to cyclists; educational marketing campaigns can raise awareness, correct misinformation to reduce unsafe driver/cyclist behaviours, and promote safer ones (e.g., helmet use, vehicle maintenance, bicycle signaling knowledge, minimizing smartphone use while riding/driving, avoiding wearing black clothing); training specific to cycling and interacting with cyclists can be incorporated in graduated driver licensing programs [49]. Safety education can also be provided through mentorship programs. For example, a cycling mentorship program implemented and evaluated in Toronto, Canada increased the adoption of cycling by targeting two barriers that the research team identified: owning a bicycle (a bicycle was provided on loan) and lack of confidence riding on street (through hands-on mentorship, e.g., through rides and route planning) [50]. At the end of the 16-week program, participants reported to preferring a bike in 25% of their trips, whereas this proportion was 5% at the program entry. There was an 84% increase in how much participants were willing to spend on bicycle accessories, a control group that was also surveyed at the start and the end of the 16-week program had 4% decrease.

Regulatory laws and ***enforcement*** are fundamental for road safety and should be informed by research and supported by education campaigns. However, although research may suggest the effectiveness of an intervention, adopting it on large scale may result in different outcomes. For example, helmets are clearly beneficial to cyclist safety, but, few countries made it mandatory for cycling, including Australia where there was a decline in bicycle usage after the helmet law was introduced [51]. Further, enforcement is also important for the law to work. For example, a law requiring a license plate for bikes has been suggested in the UK to discourage aggressive and reckless riding [52]. China has implemented a similar law just for electric bikes; however, due to a lack of punishment and enforcement, 70% of 844 electric bike users surveyed indicated that they did not register a licence plate [53]. In general, although there are laws concerning cyclist behaviours, these are few and the enforcement is not sufficient, potentially leading to unsafe behaviours being common among cyclists (e.g., running red light, riding between motor vehicles). Literature suggested stronger police enforcement to penalize aberrant cyclist behaviours [54].

The following interventions have been suggested in the literature to be implemented into regulation and enforcement: (1) no right-turn-on-red as limited attentional resources of drivers can lead to conflicts with other road users and the introduction of right-turn-on-red has been found to increase crashes with pedestrian and cyclists [55]; (2) distraction engagement for cyclists, in particular smartphone use, as it has been found to be a common behaviour among cyclists and its prevalence has been found to be correlated with self-reported crash history of cyclists [30]; and (3) fines for motor vehicle intrusion to bicycle facilities without exception as this poses a risk to cyclists [11].

DISCUSSION

In this paper, we provided a review of countermeasures for improving cyclist-driver interactions and grouped them in a taxonomy in three categories: vehicle/gear, infrastructure, and policy design. It appears that, among the existing interventions, infrastructure-related ones are the most effective, in particular if they separate cyclists from motor vehicle traffic. However, it should be noted that evaluations of specific interventions are very limited. We could identify one meta-analysis paper comparing different road-layout interventions that found cycle-tracks to be one of the most effective. However, the number of studies that were included in this meta-analysis was limited and most had methodological limitations [41]. Therefore, there is a need for further evaluations of different interventions in general, and more rigorous ones in particular.

Further, technological advances now enable vehicle-to-vehicle and vehicle-to-infrastructure communication, along with artificial intelligence that can be leveraged to support driver-cyclist interactions. Although the resulting systems aimed to enhance cyclist safety are not yet mature enough, they are very promising. Infrastructure and policy design can shape the behaviour of drivers and cyclists, but vehicle technology can also help extend drivers' information processing capabilities such as overcoming the limits of visual attention. For example, a blind-spot detection system can aid drivers to detect cyclists when the drivers' visual attention is focused elsewhere, and vehicle-to-vehicle communication can help motor vehicles predict bicycle trajectories. However, with such technology, concerns for maladaptive behaviours also emerge. For example, drivers may get accustomed to having a blind-spot detection system and may lose the habit of performing over-the-shoulder checks for cyclists. Such a maladaptation would be particularly dangerous when drivers switch vehicles and need to drive a car without a blind-spot detection system.

Road transportation is a complex system with many agents. According to the systems approach for human error management, a system should have several defense barriers to prevent errors from occurring or propagating [56]. With this view, cyclist-safety programs should utilize multiple approaches and create defense barriers at the vehicle/gear, infrastructure, and policy levels. The effectiveness of a specific intervention alone may not indicate its ultimate success in a more comprehensive program. Future research should evaluate different interventions in combination.

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