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Cycling exposure and infrastructural correlates in a Flemish adolescent population

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ABSTRACT

Introduction: Infrastructure adjusted to cyclists can be used as a tool to reduce cycling crashes and injuries. To increase cycling frequency and safety, a population's cycling exposure to different infrastructure needs to be known. Since cycling behavior of adolescents cannot be compared to adults, the objective of this study is to describe the cycling exposure and the characteristics of routes used by adolescents for bicycle commuting.

Methods: We used an online travel diary to collect bicycle route information and an exposure matrix to collect cycling frequency data. Data were collected in Flanders (Belgium) from an adolescent population (15–18 years).

Results: From the 1345 participating adolescents, 47% used their bicycle at least once a week. Infrastructural correlates were based on 467,000 km of cycled roads with a mean trip distance of 5.7 ± 4.5 km; 91% of cycling exposure is on infrastructure with speed limits of 50 km/h or more and 32.7% on dedicated cycle lanes. Lower motorized traffic density was related to higher odds of daily bicycle commuting. Higher traffic densities or speed limits were related to lower odds of daily bicycle commuting, but this relationship disappeared after adjusting for presence of a dedicated cycle lane.

Conclusions: Many adolescents who commute by bicycle cycle along streets with high speed limits and no dedicated cycle lanes probably because of the low motorized traffic densities on these roads. Adolescents should avoid roads without dedicated cycling infrastructure and high speed limits since these roads have been identified as high risk. The results are region specific and therefore this study should be replicated in other contexts.

1. Introduction

There are multiple advantages of commuting by bicycle. It is an energy efficient, cleaner, and cheaper form of transport than

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driving a car or public transport (Rabl and de Nazelle, 2012). Being physically active while commuting by bicycle brings important public health advantages, as commuting by bicycle could help to prevent physical inactivity (Sahlqvist et al., 2012), obesity (Flint et al., 2014), cardiovascular disease, and a range of other poor health outcomes (Rasmussen et al., 2016). Policymakers also recognize that the infrastructure required for cycling for transport is much cheaper than the infrastructure for motorized transport or public transport (Buekers et al., 2015).

Regardless of these multiple advantages, cycling generates some concerns, such as traffic safety and risk of extra air pollution inhalation (Zuurbier et al., 2010; Jacobs et al., 2010; Beck et al., 2007; Fietsongevallen en infras, 2011; Int Panis et al., 2010). Between 2010 and 2015, the number of officially registered bicycle crashes in Belgium increased with 19.4% from 7808 to 9320 crashes (be.stat. Aantal dode and zwa, 2016). However, this increase does not indicate the real risks of being involved in a bicycle crash. Officially reported crash numbers are inaccurate (Juhra et al., 2012), and total numbers should be normalized for exposure (total distance cycled) in order to generate reliable safety statistics (Aultman-Hall and Hall, 1998; Vanparijs et al., 2015; Christie et al., 2007; Stevenson, 2014; Howarth, 1982; Roberts et al., 1997).

1.1. Exposure in cycling

Considering the bigger picture of the health and economic impact of cycling (Mueller et al., 2015), it is cost-effective to promote cycling as a mode of transport (Mueller et al., 2015). However, cycling safety needs to be improved to maximize the net health benefit. The number of studies on cycling safety increased in the last decade and several methods have been developed to estimate or calculate the exposure (cycled distance, time, frequency) parameters (Vanparijs et al., 2015). An individual bicycle trip is associated with its specific dangers related to traffic or road type (Bos et al., 2013). Therefore, the appropriate exposure parameters should be used to calculate risk (Christie et al., 2007), whether for cross-country comparisons, comparisons within the same country (Aultman-Hall and Kaltenecker, 1999; Yiannakoulias et al., 2012; Vandenbulcke et al., 2009), or analyses of different transportation modes (Mindell et al., 2012). In general, exposure parameters are used to estimate risk figures for motorized transport. Since motor vehicles are licensed and fuel is taxed, exposure parameters (total distance traveled and number of vehicles) are more readily available. For bicycle transport, collecting exposure data is more complex, it is rarely measured by governments or scientific studies as was shown by Vanparijs et al. (2015).

1.2. Infrastructure

Policymakers aim to increase cycling as a means to reduce traffic congestion, improve net health, and reduce air pollution. There is extensive knowledge on how to design safe bicycle infrastructure such as reducing motorized vehicle speed to 30 km/h (Jurewicz et al., 2016; Karndacharuk and Mc Tiernan, 2019), implementing dedicated cycling infrastructure separated from motorized traffic (DiGioia et al., 2017) and Others suggest to design conflict-free intersections. Not only the safety needs to be improved in order to increase the number of commuter cyclists but also the attractiveness and connectivity of the infrastructure. Therefore, some regions developed “cycle superhighways” connecting different cities with large separated bicycle paths, parallel to major roads with minimal road crossings and thus increasing the safety and reducing travel time. Besides dedicated cycle tracks, different types of infrastructure show conflicting results when it comes to crash risk (DiGioia et al., 2017). Since traffic can be considered as a societal phenomenon, there are many socio-economical factors that affect safety. In order to improve the cycling safety by adapting the infrastructure to its users, we need to know what type of infrastructure cyclists are currently using and how much they are using it.

1.3. Promoting commuter cycling by means of infrastructure

Time and distance are the most important factors that affect the use of a bicycle for transport and these factors can be influenced by streets connectivity and presence of bicycle specific infrastructure (Mertens et al., 2016; Yang et al., 2010, 2019). Mertens et al. (2016) studied the environmental characteristics that influence a street’s appeal for bicycle transport among adults. The authors found that the presence of a dedicated cycle lane is the best strategy to increase a street’s appeal for bicycle transport in an adult population. Verhoeven et al. (2017) studied the social and physical factors that affected cycling for transport in an adolescent population. They found that a physically well separated bicycle path is more important to adolescents compared to distance. Mulley et al. (2013) found similar results in Australia, in which study participants indicated that cycling 1 km on a busy road without bicycle infrastructure was equally attractive to cycling 2.3 km on a busy road with bicycle lanes. These studies are in line with the results of Degraeuwe et al. (2015) who found that the presence of cycling infrastructure increases the time and length of bicycle commutes by more than 40% and indicated that investing in bicycle-specific infrastructure is an effective approach to increase cycling as a transportation mode.

Throughout Europe there is a correlation between length of cycling infrastructure and cycling modal share (Mueller et al., 2018). In addition, it has been shown that bicycle-specific infrastructure can reduce injury rates between 9% and 50% (Reynolds et al., 2009). It has also been shown that cycling on dedicated cycle lanes separated from motorized traffic is safer than cycling in mixed traffic (Moritz, 1998; Rodgers, 1997). These findings continue to hold more than 2 decades later. They were confirmed by Lusk et al. (2011), who found a 38% reduction of injuries on cycle lanes compared to cycling on streets without bicycle facilities.

1.4. Different populations

It has been shown that gender and age affects cycling behavior (Useche et al., 2018, 2019; Boufous et al., 2011). Elderly take less risks compared to young adults and adolescents (Boufous et al., 2011; Feenstra et al., 2010). There are many theories explaining this difference in behavior. Some indicate young adults take more risks because they are un-experienced (Twisk et al., 2018), while others indicate it is due to a societal phenomenon (Raithel, 2001). Fact is, there is a difference in behavior between age groups and thus when optimizing cycling infrastructure, we need to consider its users. Additionally, due to the difference in behavior and experience, we cannot assume that these different age group are likely to use the same type of infrastructure (Hull and O'Holleran, 2014). Therefore, cycling exposure should be studied in different age categories. However, previous studies on cycling safety and exposure focused on adult and elderly populations, while little is known about adolescents' cycling exposure and route choices (Vanparijs et al., 2015).

1.5. Objectives and hypothesis

The objective of this study is to describe the cycling exposure and the characteristics of routes used by adolescents for bicycle commuting in a cycling population.

Based on Yang et al. (2019) and Hull et al. (Hull and O'Holleran, 2014), who showed that commuter cyclists prefer safe routes, but can be perceived differently between experienced and less-experienced cyclists, we hypothesize that adolescents will cycle on dedicated cycling infrastructures and on roads with low speed limits (30 km/h).

2. Methods

2.1. Study design

This study is part of a large prospective study among Flemish adolescents that assessed cycling exposure using a one-year follow-up study design. Initially, we contacted 15 schools with high cycling levels through e-mail and/or phone. We were invited by school board of eleven of these schools to present and promote our study. From these eleven schools, eight schools agreed to participate between November 2013 and March 2014. In total, 76 classes participated with 20–25 adolescents in each class. The researchers had two contact meetings with each participating class, one at the start of the study and the second at the end of the school year. During the first contact moment, that took 45 min, the project was explained to the adolescents. They filled out a general questionnaire (e.g., age, height, weight, socio-economic background, physical activity level), and were given an explanation of the technical aspects of the web-based travel diary, which is based on a Google Maps application. Pupils learned how to create a personalized bicycle route on Google Maps. They needed to enter their home address in the application and then an automatic route for cycling, was created. They learned how to change this predefined route according to their personal routes that they generally cycle. Some pupils stopped by a friend to cycle in group, others preferred a different route or knew a short cut. Each route was checked by the researchers during the contact moment and once their bicycle routes were entered correctly, they were saved in the application as "home-school" bicycle trip. Subsequently, pupils learned how to update their travel diary and were asked to update this travel diary once a week to provide details about their bicycle trips to school during the past week. More specifically, pupils needed to define on what days they did the "home-school" bicycle trips in the past week. During the second contact meeting, at the end of the study period, all pupils were invited to fill out a feedback questionnaire assessing their travel behavior in the past school year using an exposure matrix (Table 1, Annex 1) (Bere and Bjorkelund, 2009). The exposure matrix is a matrix whereby the subject can indicate how many times a week they used different transportation modes to make a specific trip in the different seasons, in this case commuting between home and school. This is a reliable method to assess exposure (Bere and Bjorkelund, 2009). The sum was made per transport mode in order to calculate the total number of trips per school year.

2.2. Ethical procedure

One week before the first contact moment, all adolescents received two letters, one for themselves and one for their parents. The letters included the informed consents and explained the study and its objectives. If the adolescents or their parents didn't agree to participate in the study, they had to fill out a form that stated that they did not want (their child) to participate. During the first contact moment, the project was again explained and the signed informed consents were collected. Adolescents were able to retract their participation at all time. The Vrije Universiteit Brussel ethics committee approved the study (B.U.N. 143201318030), certifying that all ethical principals were met and that the study was in accordance with the Declaration of Helsinki.

Table 1
Definition of the road characteristics and subcategories.

Traffic density	Presence of bicycle infrastructure	Speed limit
Low density: roads not included in the traffic model (minor roads) or with AAWT $\leq$ 2,500 pcu/day	Roads with any type of bicycle infrastructure, which can be a cycle lane separated from motorized traffic, a cycle lane without physical separation, or a shared lane with other traffic types	Low speed: speed limits up to 30 km/h
Moderate density: roads with AAWT between 2,500 and 10,000 pcu/day	Roads without bicycle infrastructure: roads with an empty content for the "cycle lane" attribute in open street maps (OSM)	Moderate speed: speed limited to 50 km/h
High density: roads with AAWT $\geq$ 10,000 pcu/day		High speed: speed limit above 50 km/h

2.3. Study area

Participating schools were located in the northern part of Belgium (Flanders). Flanders is a small industrialized region of 13.682 km^2 with approximately 7.5 million inhabitants. Antwerp, with approximately 500,000 inhabitants over 204 km^2, is the second largest city in Belgium after the Brussels Capital Region (BCR). The cities between Antwerp and the BCR tend to sprawl into their peripheries, leading to dense road networks. The Flanders region has a road network of 70.604 km, which comprises 4.3% of the surface (De Geest, 2011). Forty percent of the trips shorter than 3 km are done by car, 22% by bicycle, and 25% by foot (Geurts, 2014). The modal share for trips longer than 9 km is 80% by car, 3% by bicycle, and 10% by public transport.

Fig. 1 shows the population density in the Flemish region and the Brussels-Capital Region.

2.4. Measures

Adolescents filled out the travel diary at the start of the prospective period for at least one week. We encouraged them to continue doing so until the end of the school year but this data was not reliable. Therefore, only the data collected during the first week was used in combination with the exposure matrix filled out at the end of the school year to generate the exposure data. Adolescents who declared never to use their bicycle to travel to school were excluded from the study. Through individual cycling routes inputted in Google Maps, information about location, various types of road infrastructure, and trip and route choice was collected.

Two subgroups of participants were identified: those who commuted by bicycle on a daily basis (57%) during the whole school year (regular bicycle commuters) and those who commuted by bicycle at least once a week for at least one season (43%) meaning they filled out the exposure matrix and for the sum of all periods they had at least ‘1’ in the row of ‘bicycle’ (occasional bicycle commuters).

Different types of infrastructure were analyzed. To assure uniformity of our analysis, distance was used as the exposure unit.

2.5. Data processing

The travel diaries resulted in a collection of bicycle routes for each participating student. Each trip is represented by a georeferenced line object, containing information about the trip origin and destination and the route choice and thus, the trip distance. All information from the trips was retrieved with the open street maps (OSM).

In the first step of the processing, some manual checks were performed to delete or correct some (possibly) erroneous data, such as the following example:

- Most students defined different routes for the trip from home to school and for the return home from school. In this case, each route was cycled once a day. However, some students defined a single route between home and school. This second case needs special treatment in the processing, as one route was cycled twice a day (in one direction in the morning, and in the other direction in the evening); therefore, such trips was double-counted in the analysis.

In the second processing phase, these trip data were combined with geographic network data, in order to split each trip (trip length) into segments according to the characteristics of the cycled road (e.g. length of the trip cycled on roads with/without bicycle infrastructure). A list of different infrastructural characteristics that could affect cycling safety was set up. Only a limited number of characteristics could be used since with too many categories, statistical analysis would become insignificant. Additionally, the infrastructural characteristics needed to be available in OSM. After eliminating the characteristics with a lack of available data in OSM, the authors discussed and agreed to use three main characteristics: traffic density, presence of bicycle infrastructure and speed limit.

The annual average weekday traffic (AAWT) is a direct indicator of traffic density on each road, and the average number of person car units (pcu) per weekday on the given road was used as an indicator of the type of road on which the student was cycling. AAWT

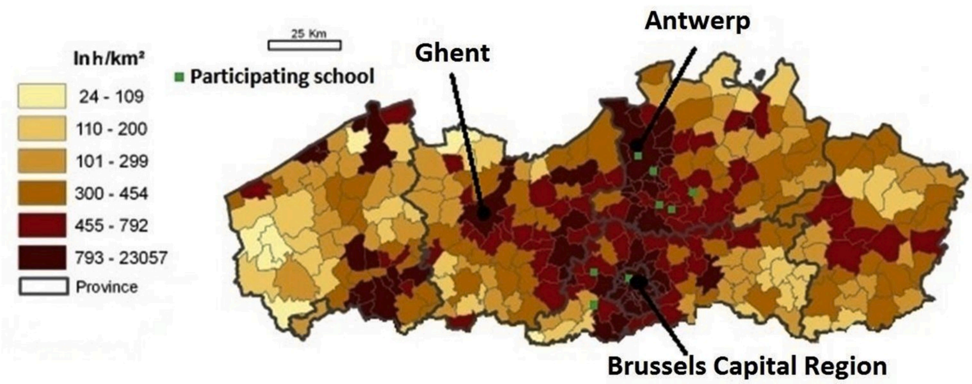

Fig. 1. Study area and location of participating schools on a population density map of Flanders and the Brussels Capital Region (Poelmans et al., 2014).

data were obtained from the strategic traffic model, which is managed and validated by the Flemish government (Bijnsgebouw, 2015) (Table 1). For the presence of bicycle infrastructure and speed limit, open street maps was used to collect information about the presence of a cycle lane. If the "cycle lane" attribute was empty, we assumed no bicycle infrastructure (Table 1). A cycle lane was defined as any dedicated cycling infrastructure which excludes cycling suggestion strips (were motorized traffic is mixed with bicycles) but includes a cycle lane on the road and separated or protected cycle lane (Figs. 2–4). The whole process of map matching was visually controlled and corrected for each trip. Therefore, no participants needed to be excluded.

As a result, the trips were segmented using three road characteristics and subcategories, as shown in Table 1.

Combining the classifications by these three attributes, a total of 3×2 x $3 = 18$ combinations are possible. The total length of the bicycle trip to/from school was segmented and each segment was distributed over these 18 classes.

In the last processing step, the length per bicycle trip (and its distribution over the road categories) needed to be converted into the total annual exposure (total annual distance of school trips by bicycle). The data per school trip, as calculated in the second step, were upscaled to an annual total by multiplying the data by the frequency of cycling to school (annual number of trips to/from school by bicycle).

This frequency was estimated for each student individually, based on the information from the feedback survey (Bere and Bjorkelund, 2009), where students were asked how many days per week on average they cycled to school in fall, winter, and spring. This differentiation facilitates consideration of seasonal variations, for example, some students cycle to school less often (or not at all) in winter. By applying these cycling frequencies to the number of school days per season, the total annual number of school trips by bicycle was estimated for each student.

Applying this number to the average trip length yields the total annual distance cycled for school trips, distributed over the different road categories.

2.6. Statistical analysis

The analyses were performed using R version 3.3.1. with a probability level set at 0.05. Descriptive statistics for the total sample and each school were calculated. To examine the relationships between the route characteristics and the bicycle commuting outcome variables, generalized linear mixed models adjusted for clustering of participants within schools were fitted using the lme4-package (Bolker et al., 2009; Bates et al., 2015).

Given that 57% of the 636 cycling participants commuted on a daily basis, the relationships between route characteristics and two different outcomes were examined: (1) relationships with the probability of daily bicycle commuting, and (2) relationships with the frequency of bicycle commuting among those who did not commute by bicycle daily. To examine the relationships between route characteristics and the probability of daily bicycle commuting, mixed logistic regression models were fitted using a stepwise procedure. This approach accounts for the complexity of the sampling design and accommodates both random and fixed effects in the model. In the first step, the relationship between each route characteristic and the probability of daily bicycle commuting was estimated for each route characteristic separately adjusted for distance. In the second step, the route characteristics shown to be significantly related to the probability of daily bicycle commuting in the previous step were entered simultaneously into a combined model adjusted for distance. The variance inflation factor (VIF) was used to test for multicollinearity; route characteristics with a VIF above 3 were excluded from the model (Zuur et al., 2010). In a third step, to examine the relationships of daily cycling commuting with the combined route characteristics "speed limit-cycling infrastructure" and "traffic density-cycling infrastructure", the same stepwise procedures as described above were followed separately for these two combined variables. The final model for "speed limit-cycling infrastructure" and "traffic density-cycling infrastructure" were adjusted for traffic density and speed limit variables, respectively, which were found to be significantly related to the probability of daily bicycle commuting in the second step.

To examine the relationships between route characteristics and the frequency of bicycle commuting among those who did not commute by bicycle daily, mixed negative binomial models were fitted. The same three-step procedure as described above was

Fig. 2. Cycle lane on road.

Fig. 3. Separated cycle lane.

Fig. 4. Cycling suggestion strip.

followed. Exponentiated negative binomial regression coefficients were presented, which can be interpreted as proportional differences in frequency of bicycle commuting related to a one-unit difference in the route characteristic.

3. Results

3.1. Participants

After explaining the protocol, 1345 pupils out of 1654 adolescents aged between 15 and 18 years, volunteered to fill out the general questionnaire and first travel diary (participation rate = 81%) (Fig. 1, Annex 2). From these 1345 adolescents, 51% lived in the province of Antwerp, 22% in Flemish Brabant province, 24% in East Flanders, and 4% in Brussels-Capital Region. The mean age of the 1345 participants was 16.3 ± 2.7 years and the mean Body Mass Index (BMI) was 20.3 ± 2.4 kg/m^2 (Table 2). The mean distance to school, based on their personalized travel diary was 6.9 ± 5.4 km.

Of the 1345 pupils who filled out the feedback questionnaire, 636 pupils (47%) reported that they commuted by bicycle at least once a week for at least one season, and thus, were included in the analysis of infrastructural correlates.

Table 2
Adolescents characteristics (N = 1345).

BMI (kg/m^2) (mean ± sd)	20.3 ± 2.4
Age (mean ± sd)	16.3 ± 2.7
Dist. School (km) (mean ± sd)	6.9 ± 5.4
Antwerp (% of participants)	51%
Brabant province (% of participants)	22%
East flanders (% of participants)	24%
Brussels-capital region (% of participants)	4%

3.2. Exposure and road characteristics

The exposure parameters are derived from a total sum of 467,115 km of cycling registered by the 636 participants who reported using their bicycle. The median trip distance by bicycle to school was 4.4 km (Q1 = 2.6 km and Q3 = 7.3 km) for the 369 adolescents who commuted by bicycle on a daily basis and 7.1 km (Q1 = 3.8 km and Q3 = 12.6 km) for the 267 occasional bicycle commuters (Fig. 5). The distribution of the trip distance was skewed: the longer the trips, the less they occurred.

From the total exposure, 64.3% was on roads with a speed limit of at least 50 km/h, 66.5% of the trips had no cycle lane, and 21.9% had high traffic density (Table 3 a&b).

Of the road segments, 11.5% had a speed limit above 50 km/h and had cycle lane infrastructure, whereas 16% had no cycle lane infrastructure. Segments with low traffic density and cycle lanes represented 5.7% and those with low traffic density but without bicycle lanes represented 45.1%. Segments with high traffic density and cycle lanes represented 17% and those with high traffic density but without bicycle lanes represented 4.9%.

3.3. Route characteristics related to daily bicycle commuting

3.3.1. Relationships between the odds of daily bicycle community and distance, traffic density, speed limit, and cycling lane presence

In the final model, three route characteristics were significantly related to the odds of daily bicycle commuting: distance, percentage low traffic density, and percentage medium speed limit (Table 4). A route of 1 km longer was associated with 10% lower odds for daily bicycle commuting ($p < 0.001$). Routes with a higher share (1%) of low traffic density and moderate speed limit were both associated with a 1% higher odds of daily bicycle commuting.

3.3.2. Relationships between odds of daily bicycle commuting and the combined route characteristics of "speed limit-cycling infrastructure" and "traffic density-cycling infrastructure"

Routes with 1% more high speed limits and no cycle lanes had 1% lower odds of daily bicycle commuting ($p < 0.05$). For route with cycle cycling infrastructure available, a higher % of streets with a high speed limit did not relate to the odds of daily bicycle commuting. Trips with 1% lower traffic density and cycle lanes were associated with a 2% increase of daily bicycle commuting ($p < 0.05$). When no cycle lane was available, low traffic density did not increase the odds of daily bicycle commuting (Table 5).

3.4. Route characteristics related to frequency of bicycle commuting among occasional bicycle commuters

No significant relationships between route characteristics (separate or combined) and the frequency of bicycle commuting among occasional bicycle commuters were observed. The annual average frequency of bicycle commuting in occasional cyclists was 2.1 ± 1.2

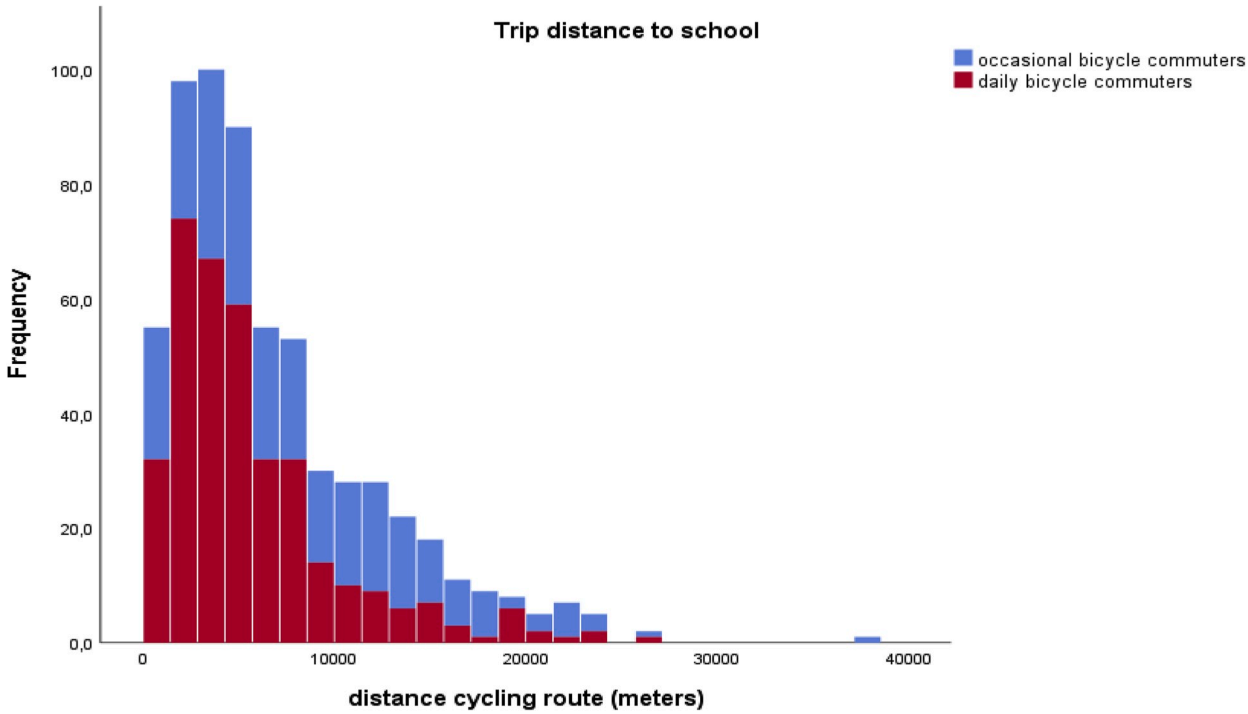

Fig. 5. Histogram on the trip distance and frequency for daily and occasional bicycle commuters.

Table 3a
Bicycle exposure per traffic DENSITY expressed in % of the total bicycling exposure.

parameter: traffic density	Total exposure	Exposure to bicyle path	Exposure without bicyle path
Traffic density: ≤ 2500 vehicles/day	50.8% (237,294 km)	5.7% (26,625 km)	45.1% (210,670 km)
Traffic density: 2500–10000 vehicles/day	27.3% (127,522 km)	10.5% (49,047 km)	16.8% (48,475 km)
Traffic density: ≥ 10000 vehicles/day	21.9%(102,298 km)	17% (79,409 km)	4.9% (22,889 km)
Total	100% (467,115 km)	33.5% (156,484)	66.5% (310,631 km)

Table 3b
Bicycle exposure per speed limit expressed in % of the total bicycling exposure.

Parameter: speed limit	Total exposure	Exposure to bicyle path	Exposure without bicyle path
Low (speed limit: ≤ 30 km/h)	8.2% (38,303 km)	0.8% (3737 km)	7.4% (34,566 km)
Medium (speed limit: = 50 km/h)	64.3% (300,355 km)	21.2% (99,028 km)	43.1% (201,307 km)
High (speed limits above 50 km/h)	27.5% (128,456 km)	11.5% (53,718 km)	16% (74,738 km)
Total	100% (467,115 km)	33.5% (156,484 km)	66.5% (310,631)

Table 4
Logistic regression for individual environmental parameters. The combined model includes all route characteristics significantly related to the odds of daily bicycle commuting in the model with the route characteristics separately and adjusted for distance.

	Models with separate procedures for route characteristics variables[a] OR(95% ci)	Combined model OR (95% ci)
Distance	N.A.	0.90 (0.87–0.93)**
% Low traffic density	1.01 (1.00–1.01)*	1.01 (1.00–1.02) *
% Moderate traffic density	0.99 (0.99–1.00)	N.A.
% High traffic density	1.00 (0.99–1.00)	N.A.
% Low speed limit	1.00 (0.99–1.01)	N.A.
% Moderate speed limit	1.01 (1.00–1.02)*	1.01 (1.00–1.02)*
% High speed limit	0.99 (0.98–1.00)*	#
% With cycle lane	1.00 (0.99–1.01)	N.A.

*p < 0.05, **p < 0.001, # VIF >3.
N.A. not applicable.
[a] adjusted for distance.

times per week. In fall and winter, the average was 1.3 ± 1.5 times a week and differed significantly from trip frequency in spring, which was 3.2 ± 1.4 times a week ($p < 0.001$).

4. Discussion

The objective of this study was to identify the exposure of adolescent cyclists to different cycling conditions in Flanders. We found a high exposure to infrastructure without a dedicated cycle lane (66% of cycle routes). Specifically, 16% of cycling exposure (in km) was on roads with speed limits above 50 km/h and without dedicated cycling infrastructure. This is the first worrying result of this study, since it has been shown that there are multiple advantages of dedicated cycle lanes (Reynolds et al., 2009; Cripton et al., 2015). An Australian study (Beck et al., 2016) found not only that the risk of injury from a bicycle crash was lower on cycle lanes but also that the severity and possibility of head injury was lower on cycle lanes. Therefore, traffic safety could be improved by creating cycle lanes separated from motorized infrastructure (Teschke et al., 2012), especially along busy streets or when the speed limit is 50 km/h or higher. 91.2% of cycling in our study is on infrastructure with speed limits of 50 km/h or higher and only a relatively small proportion (32.7%) of that is on a cycle lane. Additionally, a total of 58.5% of cycling exposure is mixed with motorized traffic riding at speed limits of 50 km/h or higher. The risk of severe injury decreases by approximately 50% when the speed limit is reduced from 50 km/h to 30 km/h or lower (Dalvi, 2004; Kim et al., 2007). This implies that, even in a region that is considered to be relatively safe for cycling such as Flanders (Silverans et al., 2015), there is still a wide margin to improve safety for adolescent cyclists.

By reducing speed limits in a larger radius around schools (e.g. the schools catchment area) and by providing dedicated cycle lanes wherever possible, safety could be improved substantially. Both the lack of dedicated bicycle infrastructure and speed limits of 50 km/h or higher show that there is a lot of potential for the Flanders government to change infrastructure not only to provide improved safety for adolescent cyclists but also to increase the cycling frequency (Verhoeven et al., 2017). The cost–benefit analysis of Steinbach et al. (2013) showed that after five years, there is a positive net present value for implementing traffic-calming measures if the number of casualties was 0.7 per km before the intervention.

The second objective of the study was to examine the route characteristics related to bicycle commuting. Before looking at the different parameters that correlate with commuting by bicycle, the specific geographical location and characteristics of the schools

Table 5
Logistic regression for combined environmental parameters including all route characteristics significantly related to the odds of daily bicycle commuting in the model with the combined route characteristics and adjusted for distance.

	Separate models for each route characteristic (adjusted for distance) OR (95% ci)	Combined (speed-cycling infrastructure) model OR (95% ci)	Combined (traffic density- cycling infrastructure) model OR (95% ci)
Distance	N.A.	0.90 (0.87–0.94)**	0.90 (0.86–0.93)**
% Low speed limit & no cycling infrastructure	1.00 (0.98–1.01)	N.A.	N.A.
% Low speed limit & with cycling infrastructure	1.02 (0.96–1.07)	N.A.	N.A.
% Moderate speed limit & no cycling infrastructure	1.00 (1.00–1.01)	N.A.	N.A.
% Moderate speed limit & with cycling infrastructure	1.01 (1.00–1.02)	N.A.	N.A.
% High speed limit & no cycling infrastructure	0.99 (0.98–1.00) †	0.99 (0.98–1.00)*	N.A.
% High speed limit & with cycling infrastructure	0.99 (0.98–1.00)	N.A.	N.A.
% Low traffic density & no cycling infrastructure	1.01 (1.00–1.01) †	N.A.	N.A.
% Low traffic density & with cycling infrastructure	1.02 (1.00–1.04)*	N.A.	1.02 (1.00–1.04)*
% Moderate traffic density & no cycling infrastructure	1.00 (0.99–1.01)	N.A.	N.A.
% Moderate traffic density & with cycling infrastructure	0.99 (0.98–1.00) †	N.A.	N.A.
% High traffic density & no cycling infrastructure	0.98 (0.96–1.00)*	N.A.	0.98 (0.96–1.00) †
% High traffic density & with cycling infrastructure	1.00 (0.99–1.01)	N.A.	N.A.
% Low traffic density	N.A.	1.01 (1.00–1.02)*	N.A.
% Moderate speed limit	N.A.	N.A.	1.01 (1.00–1.02)**

† $0.10 > p > 0.05$, *$p < 0.05$, **$p < 0.001$; N.A. not applicable.

should be considered. Taking into consideration that the participating schools are all located in relatively dens populated areas we can expect that the distance to schools will be relatively small. Additionally, we preselected 15 schools with considerable high amounts of cycling adolescents from which eight volunteered to participate. Possibly, these schools know they have a very high cycling population and therefore agreed to participate. This preselection bias and geographical location might explain the high numbers of (daily) cycling adolescents. High numbers of children cycling to school have been reported before (Cardon et al., 2012). Previous studies have shown that several parameters are correlated with commuting by bicycle, including physical environmental factors (Ducheyne et al., 2012; Fraser and Lock, 2011). We found several route characteristics that correlate with daily bicycle commuting, among which distance is the most important. The longer the trip distance between home and school, the less likely adolescents commute by bicycle on a daily basis. The average trip distance in our study was 5.7 km ± 4.5 km and 8.5 km ± 6.0 km for those who commute by bicycle on a daily basis and occasional commuter cyclists, respectively. This is a significantly longer distance than the 3 km found by D'Haese et al. (D'Haese et al., 2011), although the population in their study were primary school children (aged 11–12 years) whereas our population was aged 15–18 years. One explanation for the longer average trip distance is the increased physical capacity and responsibility in traffic (Janz et al., 2000) of secondary compared to primary school children.

The second parameter that correlates with commuting by bicycle is traffic density. Lower traffic density increased the odds of daily bicycle commuting. Possibly, the route is perceived as safer when motorized traffic density is lower. Another advantage of low traffic density is the associated ease of mind when cycling in a quiet environment.

A third parameter in our study that affects the odds of daily bicycle commuting is the maximum speed limit for motorized traffic. When trips contain larger parts with high speed limits (above 50 km/h), the odds of daily bicycle commuting decrease. However, this negative impact is cancelled out when there is a dedicated cycle lane. These results are in line with other studies in which safety perception was found to be related to cycling or walking to school (Verhoeven et al., 2017). Mertens et al. (2016) found that when a dedicated cycle lane was available, other safety parameters, such as speed limit, presence of traffic calming measures, and traffic density, did not affect the appeal to commute by bicycle as much as aesthetic parameters, such as vegetation or general upkeep. When it was not feasible to provide a cycle lane, safety parameters, such as speed limit and traffic density, were more effective in increasing the appeal of commuting by bicycle than aesthetic parameters.

Adolescents who commute by bicycle occasionally (not on a daily basis) have a significantly longer trip distance than daily bicycle commuters (8.5 km ± 6.0 km and 5.7 km ± 4.5 km, respectively). Weekly trip frequency for occasional bicycle commuters differed significantly between spring and winter (3.2 ± 1.4 times a week and 1.3 ± 1.5 times a week, respectively). This can be explained by the increased exposure to bad weather in winter. When trip distance increased along with exposure in the winter, adolescents preferred alternatives, such as public transport. The association between weather and cycling for transport has been studied before, and rain has been cited as one of the most important impediments to bicycle commuting (Chang and Chang, 2008). Other impediments are distance, safety, and available infrastructure.

Considering the cycling exposure and the characteristics of routes used by adolescents for bicycle commuting, it seems that regardless of the parameters increasing the odds of bicycle commuting (distance, traffic density, and speed limit), still, 59% of bicycle exposure (in km) is on roads with speed limits of 50 km/h or higher without bicycle specific infrastructure. Our result may be explained by cycling exposure on roads with low traffic density. These roads in rural environments are often perceived as "safe" roads, since there is a low exposure to motorized traffic. Unfortunately, there are no studies analyzing the crash risk for this specific type of infrastructure but the safety perception may be false, since a secondary road with higher traffic density but dedicated bicycle-specific infrastructure is associated with the lowest risk (Reynolds et al., 2009). Therefore, an information campaign could raise awareness among adolescents about the false safety perceptions on tertiary roads with low traffic density, high speed limits and no bicycle infrastructure.

Handy et al. (2014) stated the necessity to look for strategies to increase cycling. Several studies have shown the positive impact of dedicated cycling infrastructure and built environment on commuter cycling (Verhoeven et al., 2017; Ghekiere et al., 2014, 2016; Keall et al., 2015). However, we could not find infrastructure or traffic correlates for occasional bicycle commuters. One possible explanation is the difference in approach. In contrast to our objective approach, previous studies often used subjective methods such as asking participants if they would take up their bicycle as transport mode if the infrastructure would be safer. Another explanation could be that there are other parameters not included in our analysis that could affect the odds of adolescents using their bicycles more frequently, such as weather, availability of a bicycle, and availability of alternative (public) transportation modes (Heinen et al., 2010). Future studies should investigate if changes in infrastructural parameters and safety perceptions may lead to increased cycling.

4.1. Limitations and practical implications

Some limitations must be considered when interpreting the results of the study. A large number of participants did not fully complete the general questionnaire. Therefore, we did not have information about the gender of all the participants. Another drawback of the study is the method used for calculating exposure. Although the exposure matrix used in this study has been used before and showed good test-retest reliability, the exposure matrix was shown to be reliable but has not yet been validated. On top of this, a possible memory/desirability bias is present when defining the route trips from home to school. The memory bias was reduced to a minimum by helping each adolescent individually in making their personalized route. However, in the future, using a GPS tracker might reduce this possible bias Lopez Aguirre et al., 2017). Nevertheless, the exposure expressed in distance is similar to existing data of our population and, therefore, we assume that the approach is appropriate.

In this study, we focused on adolescents already using their bicycle as a transport mode. Future studies could include non-bike commuter to study differences between bike-commuters and non-bike commuters by using cycle route choice algorithms.

When interpreting the results, one should keep in mind the typical built up environment and dense road network in Flanders, especially in our research area. Additionally, the topography of our research area has very few altitude differences which also favors the use of a bicycle. Therefore, our results may not be generalizable to other regions and we encourage to replicate this study in other contexts to consolidate our results.

5. Conclusion

In the Flanders region, adolescents who commute by bicycle often use infrastructure that involve high safety risks to cyclists. In particular, the lack of dedicated cycle lanes in combination with high speed limits (which are typical tertiary roads in this geographical location) are of major concern. By reducing the maximum speed limit to below 30 km/h or by providing dedicated cycle lanes, both cycling safety and appeal would improve. Previous research has shown that human factors cause 79% of bicycle crashes in adolescent populations (Vanparijs et al., 2016). Therefore, it is even more important to reduce the risks of severe injury when a crash occurs by implementing adequate safety infrastructure.

CRediT authorship contribution statement

J. Vanparijs: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing - original draft. **J. Van Cauwenberg:** Methodology, Formal analysis, Writing - review & editing. **L. Int Panis:** Conceptualization, Methodology, Writing - review & editing, Supervision. **E. Van Hecke:** Conceptualization, Methodology. **D. Gillis:** Software, Formal analysis. **S. Gautama:** Software, Formal analysis. **R. Meeusen:** Supervision, Funding acquisition. **B. de Geus:** Conceptualization, Methodology, Writing - review & editing, Supervision, Funding acquisition.

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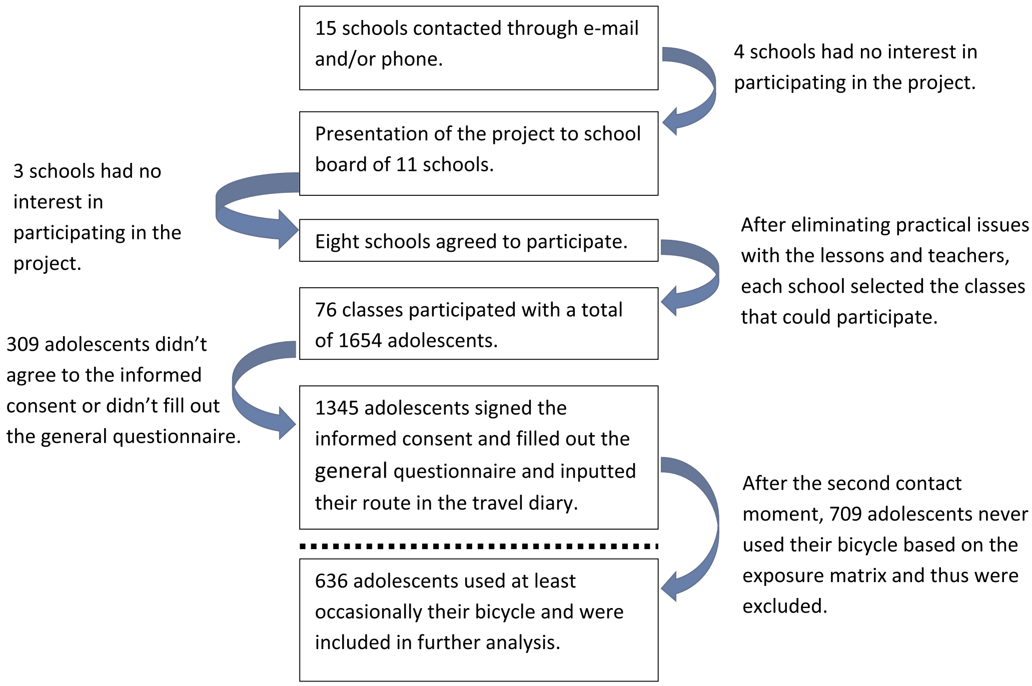
Annex 1. Exposure Matrix

How many days a week did you use each transport mode on average to go to school? Fill out the table for each period.

	Sept–Dec	Jan–March	April–June	SUM*
Foot	0	0	0	0
Bicycle	0	0	1	1 (= minimum to be included)
Car	5	5	4	14
Public transport	0	0	0	0

*column added by the researcher and not visible for the adolescents.

Annex 2. Flow chart of participants



Note: the dotted line indicates the school year

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