



On the effect of networks of cycle-tracks on the risk of cycling. The case of Seville



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ABSTRACT

We analyze the evolution of the risk of cycling in Seville before and after the implementation of a network of segregated cycle tracks in the city. Specifically, we study the evolution of the risk for cyclists of being involved in a collision with a motor vehicle, using data reported by the traffic police along the period 2000–2013, i.e. seven years before and after the network was built. A sudden drop of such risk was observed after the implementation of the network of bikeways. We study, through a multilinear regression analysis, the evolution of the risk by means of explanatory variables representing changes in the built environment, specifically the length of the bikeways and a stepwise jump variable taking the values 0/1 before/after the network was implemented. We found that this last variable has a high value as explanatory variable, even higher than the length of the network, thus suggesting that networking the bikeways has a substantial effect on cycling safety by itself and beyond the mere increase in the length of the bikeways. We also analyze safety in numbers through a non-linear regression analysis. Our results fully agree qualitatively and quantitatively with the results previously reported by Jacobsen (2003), thus providing an independent confirmation of Jacobsen's results. Finally, the mutual causal relationships between the increase in safety, the increase in the number of cyclists and the presence of the network of bikeways are discussed.

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1. Introduction

Growing public awareness about the negative effects of car-based mobility on environment and health has attracted considerable attention to alternatives based on active mobility in urban environments. Such alternatives include utilitarian cycling, that appears as a valid option for short trips below 5–10 km (Dekoster et al., 2000; Pucher and Buehler, 2012). Bicycles are also a good alternative as feeding mode for public transport networks (Martens, 2004; Dekoster et al., 2000; Pucher and Buehler, 2012). However, cyclists (as well as pedestrians) are vulnerable because they cannot benefit of the protective metallic shell of car drivers, nor can develop a comparable kinetic energy. These facts make difficult to develop appropriate traffic safety measures to protect cyclists in the street (Elvik, 2010).

Fortunately, there is a wide evidence showing that the number of bicycle traffic accidents does not grow linearly with the number

of cyclists (Elvik, 2009). Seemingly, the number of accidents varies as a less-than-one power of the number of cyclists in the streets, which implies that the risk of cycling drops when the number of cyclists increases. This effect has been named *safety in numbers* (Jacobsen, 2003; Elvik, 2009). Safety in numbers implies that policies aimed to promote cycling are also policies promoting cycling safety. However, as Wegman pointed out (Wegman et al., 2012) "... if numbers of cyclists are correlated with risk and these numbers are assumed to be the only explanation, we are in error. Large numbers of cyclists in countries such as the Netherlands, Denmark and Germany are associated with high densities of bicycle facilities. If not both numbers of cyclists and bicycle facilities are taken into account, the wrong conclusions may be arrived at. There is no solid evidence that the low fatality rates ... can only be explained by 'numbers'. Therefore, Jacobsen's conclusion may be wrong if we simply add numbers of cyclists to the system without adding safety quality, that is to say, risk reducing measures." Actually, it could happen that causality just goes in the opposite direction of what a careless interpretation of Jacobsen's analysis could suggest: There would not be more safety because there are many cyclist. Instead, there would be many cyclists because there is more safety.

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Therefore, it is necessary to analyze the effects of bicycle facilities on cycling safety. Among the aforementioned bicycle facilities, building bicycle lanes and bicycle tracks¹ are probably the most common measures (Pucher et al., 2010). Most planners and bicycle advocates (with the exception cited below) firmly believe that these facilities reduce the risk of cycling. In fact, statistics on a national scale in countries with a well developed cycling infrastructure, like the Netherlands, Denmark or Germany, point in the direction desired by such planners and cycling advocates: bicycle kilometers traveled per inhabitant continued to increase, while the number of cycling fatalities continued to decline (Pucher and Buehler, 2008a,b). However, there is a number of bicycle advocates, grouped around the *vehicular cycling* theories, which firmly believe that cycling on bike lanes and cycle tracks is less safe than cycling in the traffic. They argue that statistical evidence cannot substitute rational causality analysis and, through the analysis of a number of practical examples, try to show that cycling in the traffic is less dangerous than cycling on bikeways provided some basic skills are shared by the bicyclists (Forester, 2001; see also Puchers's reply, 2001). Although most cycling advocates does not follow such theories and support building bicycle lanes and tracks, the influence of vehicular cycling theories has been determinant for cycle traffic policies in some countries. For instance, in the USA, the guidelines of the American Association of State Highway and Transportation Officials (AASHTO) favored bicycling on roadways for many years, discouraging the implementation of cycle tracks (Lusk et al., 2013). Thus, the controversy about the actual contribution of segregated bicycle facilities to cycling safety is still ongoing (Wardlaw, 2014).

This paper presents a longitudinal study of the effect on cycling safety of the implementation of a network of bi-directional and segregated cycle tracks in the city of Seville (Spain) between 2006 and 2013. Our main motivation for this analysis was to shed light on the above mentioned controversy about the effect of cycle tracks and bikeways on cycling safety. Regarding this effect, we feel it is important to differentiate between the effect of the bikeways itself and the effect of connecting them in order to make a network covering all the area of interest. Therefore, we have developed a methodology suitable for differentiating both effects. Besides, motivated by the above mentioned Wegman's discussion about causality and safety in numbers, we also have investigated the possible causal relationships between cycling safety, the implementation of the network of bikeways and the increase in the number of cyclists associated to such implementation. Finally, we tried to obtain some practical lessons from the analysis, regarding how to increase cycling safety in cities.

We feel that the choice of Seville as a case study is appropriate because this city experienced a big growth of utilitarian cycling, from negligible values to near a 6% of all trips, after implementation of the aforementioned network of cycle tracks (Marqués et al., 2014; Marqués et al., 2015; Castillo-Manzano et al., 2015a), which was followed by the implementation of a successful system of bicycle sharing (Castillo-Manzano and Sánchez-Braza, 2013; Castillo-Manzano et al., 2015b). As far as we know, there is no other similar experience in terms of growing of utilitarian cycling in parallel to the implementation of a network of bicycle tracks. Therefore, we feel that this case study offers a unique opportunity for evaluating the effects of bicycle facilities on cycling safety and to elucidate the causal relationships involved in such process.

¹ An urban cycle track is an exclusive bicycle path alongside a city street that is separated from the motorized vehicle traffic by a physical barrier. It can run at the level of the carriageway, at the level of the sidewalk (but clearly separated from pedestrian's paths) or at an intermediate level, as in the city of Copenhagen. Bicycle lanes are exclusive bicycle paths separated from the motorized traffic by a white or colored line, or by any other mark painted on the pavement.

The analysis spans over the whole period 2000–2013 (i.e. seven years before and seven years after the implementation of the bike-ways network). We analyze the time evolution of the risk of cycling in the city, studying the relations between this variable and the main possible causes and/or consequences of such evolution, i.e. the presence and the length of the bikeways network, and the evolution of the number of bicycle trips, including the possible presence of a safety in number effect as it was reported by Jacobsen (2003) and Elvik (2009). Finally, changes in other meaningful variables, such as the percentage of Killed or Seriously Injured (KSI)² cyclists over the total number of bicycle traffic accidents, are also briefly discussed.

The paper is organized as follows: In Section 2 we present a review of the existing literature regarding the effects of bikeways on cycling safety. In Section 3 we present and discuss the main data supporting our study and develop the methodology for the analysis of such data. In Section 4 we present the main numerical results of our analysis. In Section 5 we discuss and interpret these results. Finally, in Section 6, the main conclusions of our work are presented.

2. Literature review

Despite the evidence of the positive effect of bikeways on cycling safety coming from statistics at the national level (Pucher and Buehler, 2008a,b), the evidence coming from the microanalysis of specific infrastructures is much lower. In a review dated on 2009 (Reynolds et al., 2009), Reynolds and co-workers analyzed 23 papers dealing with the effects on bicycle safety of several kinds of bicycle infrastructures and indicated that the literature on the topic was very sparse. They also highlighted that only a few types of infrastructures were studied at that time. Among the infrastructures not studied before 2009 were cycle tracks (except at roundabouts). Notwithstanding, the general conclusion of the review was that “purpose-built bicycle-only facilities (e.g. bike routes, bike lanes, bike paths, cycle tracks at roundabouts) reduce the risk of crashes and injuries compared to cycling on-road with traffic”.

A more recent review (Thomas and DeRobertis, 2013) specifically devoted to cycle tracks analyzed 23 papers dating from 1987. The review pointed out that only four of such papers (Welleman and Dijkstra, 1988; Wegman and Dijkstra, 1988; Gårder et al., 1994; Lusk et al., 2011) included exposure in the analysis, something that is essential for risk evaluation. From these four papers, only one was relatively recent (Lusk et al., 2011). The remaining three papers dated from more than 20 years ago. The papers from Welleman, Wegman and Dijkstra (Welleman and Dijkstra, 1988; Wegman and Dijkstra, 1988) were focused on bicycles and mopeds (which were allowed to ride in cycle tracks at that time in the Netherlands) and reported a general improvement of safety for bicyclists on cycle tracks but not for moped riders. They also found that most injuries in cycle tracks occur at intersections and recommended to end the cycle tracks before intersections, a practice that is not presently recommended in the Netherlands (see, for instance, Ploeger et al., 2007). The paper from Gårder et al. (1994) also concluded that cycle tracks may enhance safety between intersections, but not at intersections, and also recommended to end the cycle tracks before intersections. The overall conclusion of Gårder's paper was that cycle paths increase the risk “in average”. The paper from Lusk and co-workers (Lusk et al., 2011) compared accident rates in several two-ways cycle tracks built in Montreal (Canada) with some reference streets, and concluded that this ratio in streets with cycle tracks was 0.72 times the corresponding ratio for the reference

² “Severely injured” is defined as those victims who need hospitalization for more than 24 h.

Table 1

Summary of different specific studies about the impact of bikeways on cycling safety. The columns of the table show the authors of the study, the date, the place of the study, the type of analysis (longitudinal, cross-sectional or review) and the main conclusions of the study (positive, negative or neutral) regarding the impact of bikeways on cyclist's safety.

Author(s)	Year	Place of study	Type of analysis	Main conclusion
Welleman and Dijkstra	1988	The Netherlands	Review	Positive between intersections but negative at intersections.
Wegman and Dijkstra	1988	The Netherlands	Review	Positive between intersections but negative at intersections.
Gärder	1994	Sweden	Review	Negative in overall, but positive between intersections.
Pasanen	2001	Helsinki	Cross sectional	Negative.
Jensen	2007	Copenhagen	Longitudinal	Negative (however, exposure was not controlled).
Agerholm et al.	2008	Western Denmark	Longitudinal	Negative (however, exposure was not controlled).
Reynolds et al.	2009	N/A	Review	Mainly positive.
Lusk et al.	2011	Montreal	Cross sectional	Positive.
Teschke et al.	2012	Toronto and Vancouver	Longitudinal	Positive
Chen et al.	2012	New York	Longitudinal	Neutral (possibly positive after exposure analysis)
Nosal and Miranda-Moreno	2012	Montreal	Cross sectional	Positive
Thomas and DeRobertis	2013	N/A	Review	Positive
Lusk et al.	2013	USA (19 cities)	Cross sectional	Positive
De Rome et al.	2014	Australia Capital Territory	Longitudinal	Positive

streets, thus showing a positive impact of cycle tracks on cycling safety. The volume of cycle traffic on cycle tracks was also higher than in the reference streets. Therefore, in the frame of Lusk's study, the positive impact of cycle tracks on cycling safety could be a matter of safety in numbers (or vice versa, according Wegman's discussion). A subsequent paper from the same authors (Lusk et al., 2013) analyzed 19 cycle tracks in the USA and reported that the accidents ratio on these bikeways was substantially lower than published rates for cyclists riding on the carriageway. Both Lusk's papers are cross-sectional studies comparing different streets and did not included any before and after analysis on the same streets. A longitudinal study (Teschke et al., 2012) made at Toronto and Vancouver (Canada) also reported a substantially lower risk for bicyclists riding on quiet streets and on busy streets with cycling infrastructure than for bicyclists riding on busy streets without bicycle facilities.

Other papers also reviewed by Thomas and DeRobertis (2013) reported quite uneven results. The most critical report with regard to safety on cycle tracks was a paper coming from the Helsinki City Planning Dept. (Pasanen, 2001). This paper reported that 45% of cycled km in Helsinki (500,000 inhabitants) were on two-ways cycle paths, while 56% of accidents take place on such cycle paths. The report concluded that more than a half of the 800 km of two-ways cycle paths of Helsinki are "dangerous". Like Lusk paper, Pasanen report does no included any before and after analysis, comparing the situation in Helsinki before and after the network of cycle paths was built.

Two before and after studies were reviewed by Thomas and DeRobertis (2013). A study (Jensen, 2007) made at Copenhagen (Denmark) reported that building cycle tracks resulted in a 10% increase in bicycle traffic crashes and injuries, in a 20% increase in bicycle/moped traffic and a 10% decrease in motor vehicle traffic. Another before and after study carried out also in Denmark (Agerholm et al., 2008) found that the implementation of cycle paths resulted in a 25% increase of traffic accidents for moped riders, bicyclists and pedestrians, most of them at intersections. Nor Jensen's nor Agerholm's studies controlled for the volume of bicycle traffic. Therefore, it can be guessed that considering this exposure would have likely changed the results and conclusions of these studies (Thomas and DeRobertis, 2013).

Other studies not included in the aforementioned review were recently developed in New York (Chen et al., 2012), Montreal (Nosal and Miranda-Moreno, 2012) and in the Australian Capital Territory (De Rome et al., 2014). Chen et al. (2012) studied the impact of the implementation of cycle lanes in some streets of New York by comparing data before and after the installation of these cycle lanes. They concluded that the installation of the cycle lanes did not lead

to an increase in the number of bicycle traffic accidents "despite the probable increase in the number of cyclists". In Montreal, Nosal and Miranda-Moreno (2012) studied the cyclist's injury rates for a set of four cycle tracks and four bicycle lanes and compared them to injury rates for nine control streets. They concluded that, in overall, riding on bicycle paths was safer than riding on the control streets. In the Capital Territory of Australia, De Rome et al. (2014) interviewed cyclist that have been involved in a traffic crash, concluding that fewer cyclists were injured in on-road cycle lanes than in other cycling environments.

The results from the above mentioned studies are summarized in Table 1. These results confirm that, as mentioned above, meso- and micro-analysis at the local level are much less conclusive with regard to the positive effects of bikeways on cycling safety than one might expect from statistics at a national scale. Therefore, it is necessary to continue developing studies on the effectiveness of bicycle paths at the meso- and micro-levels, i.e. at cities and at some selected infrastructures, in order to elucidate the actual effect of each specific bicycle facility on cycling safety, and how this effect is produced.

3. Data and methodology

The data used in our analysis are shown in Table 2. We use as a primary source for bicycle traffic accidents the microdata database of the Spanish Traffic Authority (*Dirección General de Tráfico*, DGT). These microdata are collected by the traffic police on the site of the accident. They include data on the vehicles and/or pedestrians involved in the accident, as well as the victims of the accident and if these victims were or not KSI. These data are shown in Table 2 for bicycle accidents (columns 2–7). The table also shows the total length (km) of the network of cycle tracks and the number of bicycle trips (millions), as well as the risk of cycling, defined with regard to collisions between bicycles and motor vehicles for the reasons explained below.

The evolution of the city's cycle track network was described by some of the authors in some previous works (Marqués et al., 2014, 2015). In 2006 and before the city had 12 km of unconnected cycle tracks, plus 7 km of shared paths for recreational purpose along the Guadalquivir River. Along the year 2007 the Municipality built 65 km of new cycle tracks, so that the city had a network of 77 km of cycle tracks (see Marqués et al., 2015; Fig. 1). In 2013 the length of the network reached 164 km, from which 152 were cycle tracks and the remaining 12 km shared paths, most of them for recreational purpose. People allowed to ride on cycle tracks in Seville are cyclists, skaters (not skateboards) and disabled people who use wheelchairs. In practice, however, almost all users are cyclists.

Table 2
Bicycle traffic accidents recorded in the city of Seville by the traffic police (columns 2–7), risk of cycling as it is defined in the text (Risk-MV), total number of km of cycle tracks and millions of bicycle trips each year. Traffic accidents include the total number of bicycle accidents, the yearly number of cyclists killed or seriously injured (KSI) in such accidents, the total number of collisions with motor vehicles (Bicycle-MV), the number of cyclists KSI in such accidents (KSI-MV), the number of collisions with pedestrians (Bicycle-peds), the number of collisions between cyclists (Bicycle-bicycle) and the number of bicycle traffic accidents with no other vehicle involved (Bicycle only). Asterisks (*): Estimations assuming that the volume of bicycle traffic was unchanged between 2000 and 2006.

Year	Bicycle accidents	Cyclists KSI	Bicycle-MV	KSI-MV	Bicycle-bicycle	Bicycle-peds.	Bicycle only	Risk-MV	Km of cycle tracks	Million trips
2000	54	4	52	4	0	2	0	17.02*	12	3.055*
2001	65	8	64	8	0	0	1	20.95*	12	3.055*
2002	54	9	53	9	0	1	1	17.35*	12	3.055*
2003	59	7	58	7	0	1	0	18.99*	12	3.055*
2004	57	5	54	4	0	0	3	17.68*	12	3.055*
2005	42	1	38	0	0	1	3	12.44*	12	3.055*
2006	56	3	48	3	1	2	5	15.71	12	3.055
2007	56	3	48	2	1	2	5	7.4	77	6.486
2008	82	10	68	10	3	4	7	7.33	92	9.283
2009	139	11	117	9	6	9	7	8.37	105	13.983
2010	134	3	109	3	4	12	9	6.74	120	16.168
2011	93	1	81	1	3	5	4	4.75	133	17.038
2012	86	4	72	4	4	7	3	4.24	144	16.967
2013	126	6	100	6	5	7	14	6.12	152	16.333

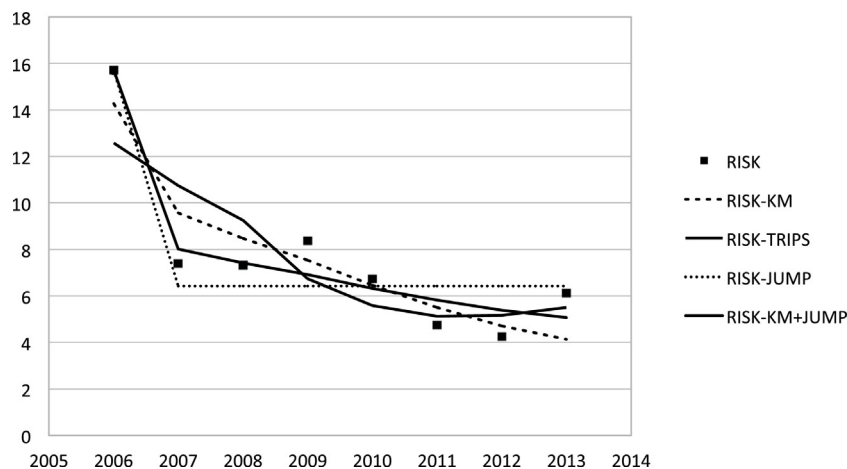


Fig. 1. Graphical representation of the results of the different linear regression models of Table 5.

Table 2 also includes the total number of bicycle trips in the city, which were computed from 2006 to 2013 using the methodology reported by Marqués et al. (2015) and subsequently by Hernández-Herrador et al. (2014). This methodology basically consisted in measuring, from counts at some representative places of the city (mainly on the cycle track network), the percentage of trips made on public and private bicycles. Since the total number of trips (rentals) made on public bikes is recorded daily by the operator of the public bike sharing system, the total number of trips made on any kind of bicycle can be easily extrapolated from these data and from the measured percentage of trips on public bikes. This methodology began to be used in 2011. For years before 2011, we used the counts made by the municipality, and estimated the evolution of the total number of bicycle trips from the average daily bicycle traffic measured in such counts (Marqués et al., 2015).

Unfortunately, before 2006 there were no bicycle counts nor other data available. However, the count made in 2006 – from which the total number of trips in such year was estimated – was made before the bikeways network was built. Therefore, we hypothesize that the total number of yearly bicycle trips in the city for the whole period 2000–2006 remained approximately unchanged. Data based on this hypothesis are marked with an asterisk in Table 2.

Finally, the risk of cycling is defined as the number of collisions between bicycles and motor vehicles per million of bicycle trips. Usually, risk is defined as the number of collisions per cycled km

(Jacobsen, 2003). This last quantity can be deduced, in fact, from our estimation (Marqués et al., 2015) of the average length of bicycle trips in the city, which was around 5 km per trip. However, we prefer to use the former definition because it is more directly linked to the available data on the volume of bicycle traffic in the city.

An important aspect regarding the interpretation of the data of Table 2 that deserves some discussion is the underreporting of bicycle traffic accidents by traffic police. There is always some underreporting of traffic accidents in the records of the police, and some studies (see Harris, 1990; for instance) claim that the report ratio (the ratio between the reported and the actual number of accidents) can be quite low. Unfortunately, we have not any indication about the value of such ratio for bicycle traffic accidents in Seville during the analyzed period. However, collisions between bicycles and motor vehicles were recorded mainly in the carriage-way (obviously cars are not allowed to ride on cycle tracks) by (almost) the same traffic policemen using the same methodology over the whole period 2000–2013. Therefore, we can assume that the report ratio for collisions between bicycles and motor vehicles remained approximately constant over such period. On the basis of this assumption, it can be concluded that the number of bicycle and motor vehicle collisions recorded by the traffic police is a good indicator (except by a time-independent constant) of the actual number of such collisions in the city. Therefore, since we are interested in the time evolution of risk rather than in their absolute value, it is methodologically correct, in the frame of such analysis, to define

risk as the ratio between the total number of collisions between bicycles and motor vehicles reported by traffic police, and the number of bicycle trips each year. This “risk” is shown in the ninth column of Table 2 using millions of bicycle trips as the unit for trips.

Risk of cycling could also had been defined as the ratio between the total number of bicycle traffic accidents and the total number of bicycle trips each year. However, as it can be seen in Table 2, the relative number of bicycle accidents other than collisions with motor vehicles increased after 2006. This change seems natural, due to the concentration of cyclists in the cycle paths and the location of many cycle paths on or next the sidewalks (Marqués et al., 2015). However, since traffic policemen could be less likely to report collisions with pedestrian or with other bicycles (which may happen outside the carriageway) than collisions with motor vehicles (which usually happen on the carriageway), this different likelihood could have changed the report ratio for all kind of accidents before and after 2006. For this reason, we prefer to define risk with regard only to collisions with motor vehicles, whose report ratio has very likely remained unchanged before and after 2006, as it was explained before. Since collisions with motor vehicles are anyway the most frequent and also the most dangerous bicycle traffic accidents (see Table 2), we feel that this definition still captures the most essential features of the risk of cycling. An additional advantage of this definition is that it facilitates the direct comparison with the available analyses on risk and safety in numbers (Jacobsen, 2003; Elvik, 2009) which also focused on collisions between bicycles and motor vehicles.

Data in Table 2 shows a clear change of tendency after 2006, when the bikeways network started to operate. There was a sudden increase in the yearly number of bicycle trips and in the yearly number of bicycle accidents. However, the risk of cycling experienced a negative jump from values around 17 to values around 7 or less. This sudden drop could be related to the sudden increase in the length of available cycle tracks and/or the increase in the number of bicycle trips, according to the safety in number theory. Moreover, since the cycle paths existing before 2007 were few and unconnected, there was a qualitative change between 2006 and 2007, with the apparition of a cycle network interconnecting the city. Thus, the aforementioned drop of the risk could be also related to this qualitative change in the built environment.

In order to elucidate these relationships, we develop a multilinear regression analysis with the risk of cycling as dependent variable and the length of the bikeways network, the number of bicycle trips in the city, and a stepwise jump variable taking the values 0/1 before/after the bikeways network was built, as explanatory variables. By introducing this last variable we want to include in the analysis the possible effect of the creation of the bikeways network by itself, as a possible cause different from the total length of bikeways.

As we mentioned in the introduction, our analysis spans over the whole 2000–2013 period (i.e. seven years before and seven years after the implementation of the bikeways network). However, since trip and risk data for years before 2006 come from an unchecked (although reasonable) hypothesis, the analysis is first developed for the period 2006–2013, and then is repeated for the whole period 2000–2013, checking for the consistency of the results.

In order to check for the accuracy of the “safety in numbers” theory, as it was reported by Jacobsen (2003), we develop a nonlinear regression analysis with different powers of the number of trips as explanatory variable, and search for the value of the exponent that minimizes the absolute value of the constant term (see next section for a more detailed explanation). Finally, we briefly analyze the changes in other meaningful variables, such the percentage of KSI cyclists over the total number of bicycle traffic accidents. More

Table 3

Acronyms and definitions for the variables used in this study.

Variable	Definition
RISK	The risk of cycling, defined as the total number of accidents involving at least a bicycle and a motor vehicle in the DGT database, divided by the millions of bicycle trips each year.
KM	The total length of cycle tracks in km.
TRIPS	The millions of bicycle trips each year
JUMP	This variable is =0 in 2006 (and before) and =1 in the period 2007–2013.

Table 4

Pearson's correlation coefficient between the different variables considered in this section.

	KM	TRIPS	JUMP
RISK	−0.920	−0.813	−0.922
KM	1	0.944	0.825
TRIPS		1	0.696
JUMP			1

details about the methodology will be given along the following section as they become necessary.

4. Analysis and results

4.1. Multilinear regression analysis

4.1.1. Period 2006–2013

In this section we examine the evolution of the risk of cycling in the above period as a linear function of the total length of the mesh of cycle-tracks, the total number of trips (millions) and the aforementioned jump function. The considered variables are shown in Table 3.

Table 4 shows the Pearson's correlation coefficients between the variables of Table 3 in the period 2006–2013. As expected, the table evidences a high and negative correlation between the risk of cycling and the explanatory variables. The correlation with risk is higher for the length of the bicycle mesh and for the jump variables than for the number of trips. There is also a high correlation between the explanatory variables, which makes difficult the task of choosing among them. The highest correlation is between the length of the mesh and the number of trips and the lowest correlation is between the jump variable and the number of trips.

In order to explain the behavior of the RISK variable we propose a multilinear regression model with the equation:

$$\text{RISK} = a_0 + a_1X_1 + a_2X_2 + \dots \quad (1)$$

where a_0, a_1, a_2, \dots are parameters and X_1, X_2, \dots refer to anyone of the explanatory variables, KM, TRIPS or JUMP.

The different models are named with the name of the dependent variable (RISK) followed by the names of the explanatory variables included in the model, in the same order as they are included in (1). Table 5 shows the results for the most meaningful models, which are the three single-variable models and the model with the two variables KM and JUMP. Other models with two variables give worse results and were not included in the table. The model with the three explanatory variables (KM, TRIPS and JUMP) does not give statistically meaningful results different from those of the RISK-KM + JUMP model shown in the table. The results of the four models shown in Table 5, altogether with the actual values of RISK, are shown in graphic form in Fig. 1.

Models in columns 2–4 of Table 5 are single-variable models, with the variables KM, TRIPS and JUMP, respectively. The model in the last column is a two-variables model with $X_1 = \text{KM}$ and $X_2 = \text{JUMP}$. Parameters shown are the values of the different coefficients in Eq. (1), its standard errors, the coefficient of determination

Table 5

Parameters of the most relevant linear regression models (Eq. (1)) for the period 2006–2013.

	RISK-KM	RISK-TRIPS	RISK-JUMP	RISK-KM + JUMP
a_0	15.141	14.202	15.712	16.183
σ	1.417	2.090	1.488	1.131
a_1	−0.072	−0.533	−9.290	−0.039
σ	0.013	0.156	1.590	0.016
a_2				−5.143
σ				2.106
R^2	0.847	0.661	0.850	0.930
F	33.146***	11.713**	34.1203***	33.271***
ΔR^2				0.083
$F(\Delta R^2)$				5.966*

Table 6

Parameters of the linear regression models (Eq. (1)) for the period 2000–2013. The parameters listed in the table are the same as in Table 5.

	RISK-KM	RISK-TRIPS	RISK-JUMP	RISK-KM + JUMP
a_0	17.957	18.841	17.162	17.633
σ	0.950	1.342	0.814	0.877
a_1	−0.095	−0.839	−10.739	−0.039
σ	0.011	0.130	1.151	0.031
a_2				−6.593
σ				3.464
R^2	0.859	0.777	0.879	0.894
F	73.315***	41.715***	87.000***	46.478***
ΔR^2				0.035
$F(\Delta R^2)$				3.622*

R^2 of the model and the F -values of the F -distribution for each model. The last two files show the increment of R^2 and the corresponding F -value of the RISK-KM + JUMP model with regard to the RISK-KM model.

Table 5 shows that the RISK-TRIPS model is actually the worse single-variable model. The basic RISK-JUMP model is the single-variable model that shows the best numerical performance. However, this model cannot, by construction, reproduce any variations of cycling safety after 2007, which is a very important drawback of this probably too simple model. The RISK-KM model also shows a good numerical behavior, close to the RISK-JUMP model, and can take into account variations of the risk of cycling after 2007. Therefore, we choose this model as the starting point for developing models with two variables.

As we mention above, among the two-variables models, the RISK-KM + JUMP model shows the best numerical behavior. This model substantially improves the numerical performance of the RISK-KM model, with a confidence level higher than 90%, as it is shown in the last column of Table 5 (incidentally, the equivalent RISK-JUMP + KM model also improves the RISK-JUMP model with a confidence level also higher than 90%). Qualitatively, the RISK-KM + JUMP model substantially improves the ability of the RISK-KM model for reproducing the big drop of the risk of cycling between 2006 and 2007, as can be seen in Fig. 1. Therefore, we can conclude that the RISK-KM + JUMP model is the best model in the frame of the proposed multilinear regression analysis.

4.1.2. Period 2000–2013

The data for the RISK in the period 2000–2005 shown in Table 2 are based on the hypothesis that the yearly number of bicycle trips was constant over such period. Although it is a reasonable hypothesis since no changes in the bicycle infrastructure happened over such period, we did not consider these data in the previous section because this hypothesis cannot be checked independently. However, once we have a picture of the evolution of the risk of cycling in the period 2006–2013, it can be of interest to check for the consistency of such picture with the estimated data for the whole 2000–2013 period, assuming the aforementioned hypothesis. Table 6 shows the results of the multilinear regression analysis for such period, assuming that the number of bicycle trips remained constant over the period 2000–2006, as it is shown in Table 2.

In addition to Table 6, Fig. 2 shows these results in a graphic form. By comparing Table 6 with Table 5 it can be seen that the parameters a_i of the different models are very similar. The accuracy of the different models shown in Table 6 is slightly worse than for the models shown in Table 5, something that could be due to the inaccuracy of the assumed hypothesis for the number of trips in the period 2000–2006. However, the different models still describe the evolution of the risk with good accuracy, and the qualitative considerations made in the previous section about the relative explanatory value of the different models still hold. Thus,

we can conclude that the analysis for the period 2000–2013 is consistent with the analysis for the period 2006–2013, provided the yearly number of bicycle trips is assumed constant in 2006 and before.

4.2. Safety in numbers

The previous work of Elvik (2009) proposes a non-linear relation between the number of bicycle–motor vehicle collisions and the number of motor vehicles and bicycles in the streets given by:

$$\text{Number of bicycle accidents} = \alpha \cdot Q_{MV}^{\beta_1} \cdot Q_{CYC}^{\beta_2} \quad (2)$$

where α is a constant, Q_{MV} is the number of motor vehicles in the street, Q_{CYC} is the number of bicyclists in the street, and β_1 , β_2 are some positive exponents smaller than one. For the considered period of analysis (2006–2013), we can assume that variations in the number of bicyclists Q_{CYC} were much higher than variations in the number of motor vehicles. Therefore, variations in Q_{MV} can be neglected and this last quantity embedded in the constant. Regarding risk, all these considerations lead to an exponential dependence with the volume of bicycle traffic of the kind (Jacobsen, 2003):

$$\text{RISK} \approx \alpha' \cdot Q_{CYC}^{(\beta-1)} \quad (3)$$

where α' is a new constant that includes the effect of the number of motor vehicles and the exponent lies between zero and minus one: $0 > \beta - 1 > -1$.

In order to check for the accuracy of this hypothesis, we will assume a linear dependence of RISK with some negative power of TRIPS (which can be considered as a good measure of the volume of bicycle traffic) of the kind:

$$\text{RISK} = a_0 + a_1(\text{TRIPS})^{(\beta-1)} \quad (4)$$

At this point it is important to realize that the presence of the constant term in Eq. (3) implies the presence of a linear term in Eq. (2), which is at odds with the safety in numbers hypothesis. Therefore, we will search for the value of the exponent $\beta - 1$ leading to a version of Eq. (4) similar to Eq. (3). For this purpose, we develop a set of regression analyses with $(\text{TRIPS})^{(\beta-1)}$ as the explanatory variable, and check for the value of $\beta - 1$ that minimizes the absolute value of a_0 .

Table 7 shows the best solutions for a_0 and a_1 in Eq. (4) for the period 2006–2013 when $\beta - 1$ is varied between -0.1 and -0.9 , as well as the coefficient R^2 of the regression. The table shows that the value for the exponent giving the closest to zero value for a_0 is $\beta - 1 = -0.6$. Notably, this value is the same value previously obtained by Jacobsen (2003) from the analysis of other independent case studies.

Fig. 3 shows the results obtained from Eq. (4) for the risk of cycling in the period 2006–2013. By comparing Table 7 and Fig. 3 with Table 2 and Fig. 1, we can see that the results of the approximation given by Eq. (4) with $\beta - 1 = -0.6$ are substantially better

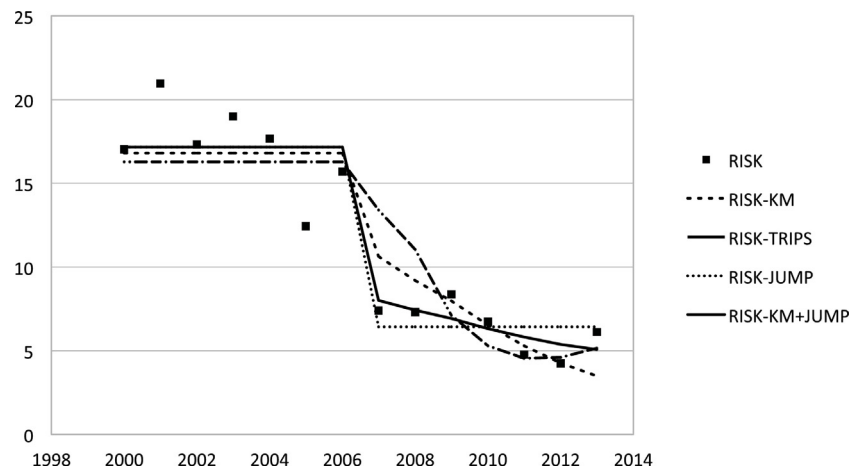


Fig. 2. Graphical representation of the results of the different linear regression models of Table 5.

Table 7

Values of the constant a_0 , the slope a_1 , and the coefficient R^2 of the linear regression Eq. (4) for values of the exponent $\beta - 1$ between -0.1 and -0.9 .

$\beta - 1$	-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8	-0.9
a_0	-41.881	-16.490	-8.045	-3.839	-1.329	0.332	1.507	2.378	3.045
a_1	62.692	38.530	31.469	28.817	28.052	28.350	29.371	30.962	33.052
R^2	0.794	0.805	0.815	0.824	0.833	0.841	0.848	0.855	0.860

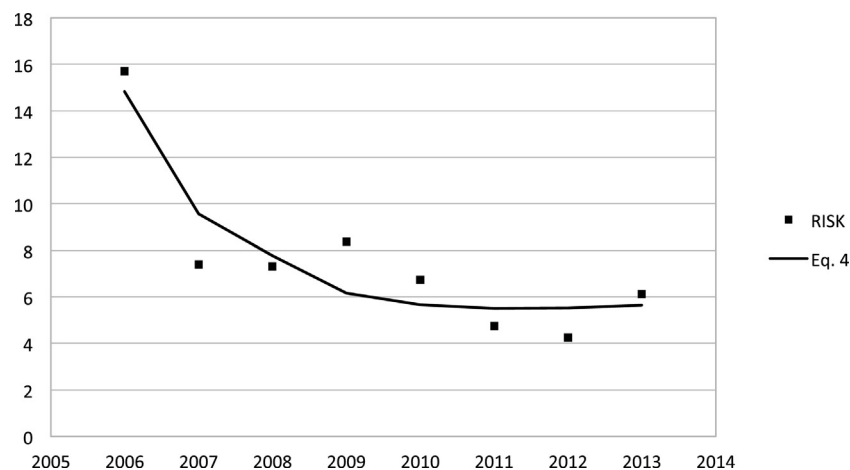


Fig. 3. Graphic representations of the results of Eq. (4) with $\beta - 1 = -0.6$.

that the results obtained from the linear model RISK-TRIPS studied in Section 3.1.1. However, they are still worse than results of the model RISK-KM + JUMP studied in the previous sections.

4.3. Additional considerations

Besides the studied risk of cycling, another meaningful indicator regarding cycling safety is the percentage of KSI cyclists over the total number of bicycle traffic accidents. The number of cyclist KSI each year is too small to develop a meaningful statistical analysis of this indicator using regression techniques. However, it would be of interest to compare the values of such indicator before and after the bikeways network was built. From Table 2 it can be easily realized that the percentage of KSI cyclists over the total number of collisions between bicycles and motor vehicles dropped from 9.5% in the period 2000–2006 to 5.9% in the period 2006–2013. This is a meaningful change, indicating that the risk of being killed or seriously injured at each collision also dropped after the implementation of the network of bikeways.

It can be also of interest to mention that similar quantitative (not shown in the paper) and qualitative results have been reached when the risk of cycling is defined with regard to all kind of bicycle accidents. That is, as the ratio between the total number of reported bicycle accidents (first column in Table 2) and the total number of bicycle trips. In fact, this result could be expected from the fact that collisions between bicycle and motor vehicles were, by far, the most frequently reported bicycle traffic accidents in the whole period 2000–2013. However, we have not focused our paper on this analysis due to our concerns about the possible variations of the report rate for the total number of bicycle traffic accidents along the whole analyzed period (see the discussion in Section 3).

5. Discussion

The numerical analysis developed in the previous section shows big changes in the risk of cycling in the city of Seville in parallel to the implementation of a connected network of segregated cycle tracks, which can be summarized as:

- Big drop of the risk of cycling after the implementation of the bikeways network, clearly associated, through a linear relation, with the variations in the length of the network.
- Relevance of the JUMP variable (=0/1 before/after the network was built) for the linear regression analysis of the evolution of the risk of cycling. This variable also remains relevant once the effect of the length of the network is taken into account.
- Nonlinear variation of the risk of cycling with the number of bicycle trips, fully consistent with the safety in numbers theory (Jacobsen, 2003).

Before to proceed with the interpretation of the above results, it would be appropriate a brief discussion on the possible contribution to the variations of the risk of other variables, such as changes in the population of the city, changes in the volume of motorized traffic, traffic calming policies or other changes in the built environment. Changes in population were not meaningful in the whole period from 2000 to 2013, where the population of the city remained more or less unchanged around 700,000 inhabitants. Regarding the influence of the volume of motorized traffic, the annual average daily traffic (AADT) in the main city avenues dropped between 2007 and 2013 by a –16%, partly due to the increase in the modal share of bicycles. A 16% is a meaningful percentage, but much less than the increase of bicycle trips, which was higher than 400%, or than the increase in the length of bikeways, which was higher than a 1000%. Therefore, it cannot be expected a contribution of changes in the AADT to the variation of the risk of cycling comparable to the contribution of the aforementioned variables. In fact, it has been numerically checked that the contribution of adding the AADT to the best model of Table 5 (RISK-KM + JUMP) is not significant, and that the contribution to the other single variable models is very small.

Traffic calming policies, such as generalized speed limits and/or shared traffic areas, have a potentially high impact on pedestrians and cyclists safety. These policies, however, were poorly developed in Seville during the analyzed period. Only for a few months in 2011 restrictions to motorized traffic were imposed in the historical center of the city, but these restrictions were soon removed after a change in the city government. Therefore, the reported drop in the risk of cycling cannot be attributed to the impact of such policies. There were, however, other meaningful changes in the built environment during the analyzed period, such as the pedestrianization of some areas, mainly at the historical center but also at some streets nearby (Castillo-Manzano et al., 2014). Since bicycle traffic on such areas was allowed, some impact of such pedestrianization on cycling safety can be expected. However, the comparative size/length of these new pedestrian areas with regard to the total length of cycle paths is small (a few km as much). Therefore, no substantial effects on cycling safety can be expected aside the already considered effects of the total length of cycle paths.

Numerical regression analyses, as well as other numerical approaches, can reveal the presence of relationships between numerical variables simultaneously measured, but they do not directly reveal the causality between them. That is, causality behind these relationships can flow, in principle, in any sense (or in both) between the different variables. An example of this concept is the discussion about causality behind “safety in numbers” already cited in the Introduction (Wegman et al., 2012). Therefore, in order to identify the causality behind the relations found in our numerical analysis, it is necessary to introduce other considerations, coming from the qualitative analysis of the “history” of the analyzed facts.

From this point of view, it becomes apparent that it was the political decision of implementing the network of bikeways which triggered the whole process leading to the reported substantial reduction in the risk of cycling after 2007 (Marqués et al., 2015). It remains, however, the question of how this causal relationship

worked. There was a direct relation between the implementation of the network and the decrease of risk, or it worked through the increase of the number of bicycle trips through a safety in numbers effect? The fact that the variables directly related to the implementation of the network of bikeways (KM and JUMP) also were the variables better related with the drop in RISK in the regression analysis, suggest that it was the implementation of the network which directly caused the big drop on risk. According to this interpretation, the main causality flow was directly from the implementation of the bikeways network to the drop of risk, and from this drop to the increase in the number of trips, according to the aforementioned Wegman’s hypothesis.

This interpretation is consistent with the specific characteristics of the network built in the city. Three main characteristics of this network were continuity, connectivity and segregation (Marqués et al., 2015). This means that the network was designed and built in order to cover, from the very beginning (just at the end of 2007), most of the whole city territory (see Marqués et al., 2015; Fig. 1 and Table 2). In addition, the whole network was segregated from motorized traffic, thus offering safe connections between all neighborhoods of the city and reducing the risk of cycling. Under these circumstances, it is not strange that many potential cyclist felt safe enough to ride their bikes through the city as an utilitarian vehicle, thus causing the subsequent big increase in the number of bicycle trips in the city.

Obviously, this interpretation must be nuanced taking into account the fact that increasing the number of cyclists in the bikeways also implies increasing the number of cyclists in the ordinary carriageway (not all streets have cycle paths and intersections are unavoidable), and that this increase of the number of cyclists in the carriageway also may produce an increase in the safety of cycling through a direct “safety in numbers” effect. Therefore, the causal relations between risk and “number of cyclists” should have been complex and bidirectional.

When we analyzed the relation between the risk of cycling and the variables related to the implementation of the bikeways network (KM and JUMP), we realized that the best correlation was with the quite simple JUMP variable, taking different values before and after the network was built. There is also a clear relation between cycling safety and the total length of bikeways, but the addition of the aforementioned JUMP variable substantially improves the model. This fact deserves some discussion. The JUMP variable was designed in order to take into account the effect of networking the bikeways as a cause different from the increase of the total length of bikeways. Therefore, we can conclude that connecting the bikeways making a network had a big impact on cycling safety by itself, and that such impact did go beyond the mere addition of the effects of each individual bikeway. Once again, this interpretation is consistent with the specific characteristics of continuity and connectivity of the cycle network of Seville (Marqués et al., 2015).

By comparing the model (RISK-KM) with the model (RISK-KM + JUMP) in Tables 5 and 6, as well as in Figs. 1 and 2, it can be realized that, apart from their different accuracy, both models predicts quite different slopes for RISK as a function of KM. That is, the model including the effect of networking the bikeways predicts a slower increase of cycling safety with the total length of bikeways once the network was built. This is an important characteristic of the model that also is in qualitative and quantitative agreement with the evolution of risk shown in Table 2. The data shown in Table 2 suggest that, basically, the risk evolved from a plateau before the network of bikeways was present to another plateau after such network was present, with a slow decay in time simultaneously to the increase in the length of bikeways. This qualitative behavior could not have been predicted so well by a model taking into account only the effect of the length of the network of bikeways (see Figs. 1 and 2). Such predictions of the model have

important consequences for the design of future planning policies aimed to further improve cycling safety. If the aforementioned RISK-KM + JUMP model is valid, this means that the benefits that could be expected from the mere extension of the network of bike-ways would be smaller or comparable to the benefits coming from other policies, such as traffic calming or restrictions to motorized traffic. Obviously, this not means that implementing the network of bikeways was useless: In fact, the effect of the JUMP variable is present because the network was built. It only means that, once the network was built, we must also look at other measures in order to further improve cycling safety.

The inclusion in the models of a variable taking into account the connectivity can be of wide interest for the analysis of the effect of bikeways on cycling safety in other contexts. For instance, it could help to explain the aforementioned gap between the analyses of the impact of bikeways on cycling safety at the macro-scale of countries and regions, and at the micro-scale of single bikeways. Since this last analysis cannot take into account connectivity, the actual contribution of the whole system of bikeways can be underestimated by such analyses. Implementing this variable in the analysis may not be a simple task. In Seville, it was because the basic network was built in just one year. Therefore, connectivity could be incorporated to the model by just using a jump variable. In other scenarios this incorporation may be more complex.

From the point of view of the design of networks of bikeways, the above analysis highlights the importance of connectivity for such design. Therefore, including such variable in the models to analyze and predict the effects of these networks, as we propose in this work, can be of key importance. Including connectivity in the models has two obvious qualitative predictions. If the network is designed with a high degree of connectivity, its short term impact on cycling safety (and therefore on the usage of the bike as an utilitarian mode of transport) will be higher than expected from the analysis of single bikeways. Conversely, once the connectivity of the network has been ensured, other measures such as traffic calming and/or restrictions to motorized traffic become more and more important for cycling safety.

6. Conclusions

The evolution of the risk of cycling in the city of Seville during the period 2006–2013 has been analyzed and, under some reasonable hypothesis, this analysis has been extended to the period 2000–2013. The aforementioned risk of cycling is defined as the yearly ratio between the total number of bicycle collisions with motor vehicles and the total number (millions) of bicycle trips. The first outcome from our analysis is the evidence of a clear drop of the risk of cycling in the city just after the bikeways network was built.

To better understanding this phenomenon, we analyzed the effects on the risk of cycling of the total length (km) of cycle tracks, of the number (millions) of bicycle trips and of an “ad hoc” jump variable which takes the values 0/1 before/after the cycle network was built. This jump variable was designed in order to include in the analysis the effect of the creation of the cycle network by itself, as a different effect from the mere increase of the length of bike-ways. The analysis shows that the best single-variable regression is with the aforementioned jump variable, followed by the regression with the length of the mesh of bikeways. The best regression with two variables includes the total length of bikeways and the aforementioned jump variable. In all cases this jump variable is present. Therefore we conclude that this “effect of the network” must be considered as a relevant effect, besides the obvious effect of the length of the mesh.

We also investigated the presence of a “safety in numbers” effect. We found that the most consistent model relating risk and number of bicycle trips was that postulating a relation between the risk and the volume of bicycle traffic through a fractional negative exponent $\beta - 1 = -0.6$. This result is in perfect agreement with the previous result of Jacobsen (2003). Therefore, our analysis provides an independent numerical confirmation of the theory of “safety in numbers” as it was previously developed by such author. Our analysis also shows that the percentage of killed or seriously injured cyclists over the total number of bicycle traffic accidents, also dropped after the implementation of the network of cycle tracks in 2007.

The causal relationships between the different variables of the model have been discussed from an historical and qualitative perspective, taking into account the main characteristics of the network of bikeways and the historical evolution of the urban environment. Our interpretation is that the primary cause for the aforementioned big drop of risk was the implementation of the network of bikeways, and that the subsequent reduction of risk was the primary cause for the increase in the number of bicycle trips. However, since not all the streets have bikeways, other more complex causal relationships should be present, such as a direct “safety in numbers” effect due to the increase in the number of cyclists in the carriageway without bikeways. Therefore, our interpretation postulates a bi-directional causal relationship between “numbers” and safety.

Our main conclusion regarding policies aimed to promote cycling safety in the city of Seville was the confirmation of the importance of the decision of creating a complete network of bikeways covering the whole city instead of just continue making isolated bikeways. Future policies aimed to further increase cycling safety in the city should, however, take into account the need of complementing the extension of the network of bikeways with other measures such as traffic calming and/or restrictions to motorized traffic, which have been yet poorly developed in the city.

We feel that our analysis sheds light on the debate about the effect of bikeways on cycling safety, highlighting the positive effect of networking such bikeways. We think that the present methodology could be also of interest for other cities that also are developing policies aimed to promote utilitarian cycling. Other topic of interest for future research is the analysis of the effect of bikeways on bicycle traffic accidents other than collisions with motor vehicles, such as accidents involving pedestrians and/or other cyclists.

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