Accident Analysis and Prevention

How does a modal shift from short car trips to cycling affect road safety?

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ABSTRACT

Governments aim to promote a shift from car to bicycle, but concerns about road safety seem to represent an important argument against this encouragement. This study examines the road safety impact of a modal shift from short car trips to cycling in Dutch municipalities. The road safety effect is estimated using Accident Prediction Models (APMs) that account for the non-linearity of risk. APMs are developed utilizing Negative Binomial regression. This study is the first to develop APMs using crash and mobility data from municipalities, and utilizing these models to estimate the effects of changing modal splits of current car and bicycle use to modal splits that actually exist in these municipalities. The results suggest that, under conditions such as in Dutch municipalities, transferring short trips made by cars to bicycles does not change the number of fatalities, but increases the number of serious road injuries. The neutral effect on fatalities, despite the high fatality risk for cyclists, can be explained by there being fewer cars on the road to pose a risk to others, the shorter length of bicycle trips compared to the car trips they replace, and the "safety in numbers" phenomenon. The rise in the number of serious road injuries is due wholly to the high number of cycling crashes with no other vehicle involved. The effect of a modal shift is dependent on the age of the population in which the shift is concentrated, and can be influenced by measures affecting cyclists' injury risk.

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1. Introduction

Policy interest in promoting a shift from car to bicycle trips has increased substantially in recent times. Car use is associated with transportation and spatial problems, such as congestion and parking difficulties, while cycling is an environmentally sustainable mode of transport with associated public health benefits (Heinen et al., 2011; De Hartog et al., 2010). For short trips up to about 7.5 km (70% of all trips in the Netherlands), many consider cycling a good alternative to car driving, as shown by the fact that 35% of such trips are made by bicycle. The car has the same share, walking has a share of 27%, and public transport is hardly used for short trips (KiM, 2011).

However, concerns about road safety would seem to represent an important argument against encouraging cycling (Elvik, 2009), given that cycling is associated with a considerably higher risk of accident-related injury than driving. For determining to what extent this argument is valid, this study uses crash and mobility data from Dutch municipalities to estimate the road safety effects of a modal shift from car to bicycle.

1.1. Factors influencing the road safety effect of a modal shift

The literature describes at least five factors about why a modal shift from car to bicycle has a smaller effect on road safety than might expected, given the higher risk of cyclists sustaining injuries compared to car occupants:

1. After shifting from car driving to cycling, individuals are less hazardous to other vulnerable road users (including cyclists) because of the lower amounts of kinetic energy expended in the event of a crash (Wegman et al., 2012).
2. Simple risk figures overestimate improvements to road safety due to replacing short car trips by bicycle trips, because the relatively safe part of long car trips, that driven on motorways, is included in the risk figures of car occupants. Across Europe, whereas 25% of the kilometres driven are on motorways, motorway accidents account for only 8% of traffic deaths (De Hartog et al., 2010).
3. Bicycle trips are often shorter than the car trips they replace (Van Boggelen et al., 2005). Drivers need to travel from low-speed access roads (i.e. local roads in residential areas) to higher speed distributor roads (i.e. arterial roads) to find the fastest route. Cyclists, on the other hand, use a more fine-grained network of roads, cycle tracks and short cuts to find their shortest

route – usually the fastest. In terms of kilometres per trip, cyclists are thus less exposed to hazards in traffic than drivers.

4. The average cyclist is safer in communities where there is more bicycling because motorists adjust their behaviour in the expectation of encountering cyclists, i.e. the "safety in numbers" phenomenon (Jacobsen, 2003).

5. Authorities may improve infrastructure safety as the amount of cycling increases (Wegman et al., 2012) and vice versa (Dill and Carr, 2003).

Given these factors, it is conceivable that a shift from car to bicycle trips would be associated with constant or even reduced crash numbers.

1.2. Estimating the road safety effect of a modal shift

Earlier studies have estimated the road safety effect of a hypothetical modal shift by multiplying the volumes of cyclists and cars before and after the change by risk figures (e.g. Stipdonk and Reurings, 2010, 2012). This method assumes a linear relationship between volumes and crashes, whereas empirical studies show that the relationship is highly nonlinear (Elvik, 2009). Consequently, it cannot account for the 'safety in numbers' effect.

Elvik (2009) was the first to estimate the road safety effects of shifts from car to bicycle (and walking) using Accident Prediction Models (APMs) in which a nonlinear relationship between crashes and volumes is assumed. In this study, we will develop and utilize APMs to model the effect of exchanging bicycle trips for car trips, taking the five factors noted above into account.

1.3. Accident Prediction Models (APMs)

Elvik used the following APM for bicycle–motor vehicle crashes:

$$BMC = \alpha Vm^{\beta 1} Vb^{\beta 2} \tag{1}$$

in which BMC is the predicted annual number of bicycle crashes Vm and Vb represent the volume of motor vehicles and cyclists. The coefficient α is a scaling parameter, which ensures that the predicted number of accidents is in the same range as the recorded number of accidents. Coefficients $\beta 1$ and $\beta 2$ describe the shape of the relationship between traffic volume and the number of accidents. The growth in crashes varies according to the value of β:

- $\beta = 1$: the growth would be linear;
- $\beta < 1$: the growth in crashes would be less than linear;
- $\beta = 0$: indicates that the number of crashes is not related to exposure.

As shown in a number of studies, either coefficient often takes on a value between 0.3 and 0.9. Elvik (2009) used similar models for other crash types that would be affected by a modal shift, using parameter estimates from existing research. The volumes of cyclists and motor vehicles before and after a hypothetical modal shift were entered into the APMs to estimate the road safety effects.

1.4. Aim of study

According to Elvik (2009), the available APMs refer only to motorized traffic in general, without distinguishing between the different types. In addition, most APMs have been developed for intersection crashes, whereas modal shifts occur across a wider area. This study aligns with and continues Elvik's research, and also adds to it in three ways:

1. It considers all the transport modes involved in car and bicycle crashes.
2. APMs are developed for municipalities as a whole so that the area where the exchange takes place coincides with the area where crashes occur.
3. Single-bicycle crashes are included. These crashes are poorly reported in official road accident statistics, although they result in high numbers of seriously injured victims (Wegman et al., 2012). The first Accident Prediction Models for single-bicycle crashes have been developed only recently (Schepers, 2011).

The remainder of the paper is organized as follows. The development of APMs is described in Section 2. Section 3 addresses the issue of distance, which is needed to estimate how many bicycle kilometres correspond to car kilometres in case short car trips are replaced by bicycle trips. Finally, Section 4 applies the models to an exchange of short car trips by bicycle trips.

2. APMs for victims in car and bicycle crashes

To determine the effect of a modal shift in Dutch municipalities from short car trips to cycling APMs were developed for the recorded numbers of deaths and in-patients – people who are hospitalized for at least 24 h – in car and bicycle crashes. Data on police-recorded crash victims in the 387 municipalities with more than 10,000 inhabitants were fitted on exponential models, using negative binomial regression modelling. This serves as statistical approximation to the crash process (Lord et al., 2005). Rural municipalities having less than 10,000 inhabitants (10% of all Dutch municipalities and home to 2% of the population) are excluded because of the low numbers of victims and the low numbers of respondents in the survey on which municipality mobility data rely. Assuming that the amount of use of transport modes other than cars and bicycles remains at the same level, the models will be based on the numbers of kilometres by car (Kc) and by bicycle (Kb) within the municipalities. Car kilometres driven on motorways are excluded because these are unlikely to be part of short car trips that could be replaced by cycling. This results in the following victim types (model form between brackets):

1. cyclist victims in:
   - bicycle–car crashes ($\alpha Kc^{\beta 1} Kb^{\beta 2}$),
   - other bicycle–motor vehicle crashes ($\alpha Kb^{\beta 1}$),
   - with no motor vehicle involved ($\alpha Kb^{\beta 1}$);
2. car occupants in road crashes: car–motor vehicle crashes and single-car crashes (αKc^{β});
3. other victims in car crashes: pedestrians, mopeds, motor cycles, vans, and so on (αKc^{β}).

There are two additional control factors: population density and the influence of age. Population density is important as it may affect both bicycle use (Dill and Carr, 2003) and the likelihood of bicycle crashes. This influence could work in two directions: where population density is low, there may be more space available for bicycle facilities; where it is high, there may be more money available to invest in facilities. Therefore, municipalities are classified into three population density classes:

- high, above 742 inhabitants per km^2;
- medium, 272–742 inhabitants per km^2;
- low, under 272 inhabitants per km^2.

Each group represents 33% of all Dutch municipalities having more than 10,000 inhabitants.

Age influences both bicycle use (Zeegers, 2010) and increased susceptibility to injury due to fragility (Li et al., 2003). For example, a low number of bicycle crashes in a college town may be the result of low cyclist age rather than high bicycle volumes. The numbers of victims and the kilometres travelled by bicycle and by car per municipality were split amongst four age groups (up to 17, 18–24, 25–64, and 65+), resulting in the data file containing one record per municipality per age group. In the regression on bicycle victims in bicycle–car crashes, the number of bicycle kilometres per municipality per age group and the number of car kilometres per municipality are used.

Using relative risk R_j for the four age groups and relative risk R_k for the three population density classes, the final models for the total number of victims per crash type used in this section have the following form:

1. cyclist victims in:
   a. bicycle–car crashes: $\sum_{jk} \alpha K c_k^{\beta 1} K b_{jk}^{\beta 2} R_j R_k$,
   b. other bicycle–motor vehicle crashes: $\sum_{jk} \alpha K b_{jk}^{\beta} R_j R_k$;
2. car occupants in road crashes: $\sum_{jk} \alpha K c_{jk}^{\beta}$;
3. other victims in car crashes: $\sum_{jk} \alpha K c_k^{\beta}$.

The control variables x_i ($i = 1, 2, 3, \ldots, n$) are modelled as an exponential function, that is, as e (the base of natural logarithms) raised to a sum of product of coefficients, y_i, and values of the variables, $x_i (e^{\sum y_i x_i})$. The exponential of the coefficients is the relative risk.

2.1. Data

Police-recorded crash data and mobility data from the Dutch National Travel Survey (NTS) are used, supplemented with route information data and Statistics Netherlands data on population density of Dutch municipalities (Statistics Netherlands, 2011). These datasets are now subsequently discussed.

2.1.1. Police-recorded crashes

Police-recorded crash data cover all recorded car and bicycle crash victims (only single-bicycle crash victims were excluded) over a six year period (2004–2009) across all 387 Dutch municipalities having more than 10,000 inhabitants. In total 2704 deaths and 40,749 in-patients are included. Police records include details on the crash location, victim characteristics, and whether the crash resulted in death or hospitalization.

2.1.2. National Travel Survey (NTS)

NTS describes the travel behaviour of the Dutch population. A sample of households is drawn every month from the Borough Basic Administration to ensure all types of travellers and households and all days are proportionately represented. Each member of the household is requested to record all journeys made on a particular day. Respondents are telephoned if they have not already responded, or to clarify missing answers; otherwise the respondent is excluded from the final data set (Ministry of Transport, Public Works, and Water Management, 2010). In total 140,852 households (317,258 persons) completed questionnaires between 2004 and 2009, corresponding to a response rate of 70.5%. The included weighting factor enables the outputs to closely reflect the Dutch population.

2.1.3. Route analyses for determining the amount of cycling and car use

To take into account the second of the five factors influencing the road safety effect of a modal shift (overestimation of the difference in road safety between short car and bicycle trips),

the amount of bicycle and car use per municipality, excluding kilometres driven on motorways, was determined. NTS notes the municipality of departure and arrival, and trip variables such as the trip length. Given the limited number of entrances to motorways and their often peripheral location in municipalities, it is reasonable to assume that motorways are rarely used for internal trips (i.e. leaving and arriving in the same municipality). Trip length is an adequate measure for the amount of kilometres for internal trips.

Nevertheless, NTS does not include route information such as which part of external trips is travelled on motorways or within the borders of a given municipality. By conducting route analyses, that part of external trips that fell within the borders of a given municipality (excluding the part travelled on motorways) was determined using Google Earth route planner service for car trips (Google, 2011) and the Dutch Cyclists' Union route planner for bicycle trips (Fietsersbond, 2011). The latter includes solitary bicycle tracks that do not run parallel to a road; Google Earth contains a layer for municipality borders. For car trips the fastest route was planned. Although drivers often plan routes that are somewhat slower, this is good approximation (Koning and Bovy, 1980). For bicycle trips, the shortest route was planned, this being a good approximation of their route choice behaviour (Gommers and Bovy, 1987).

This labour-intensive task was carried out on the 2008 NTS dataset. By exception, it was allowed (normally it is not for privacy reasons) to use a dataset containing the most detailed available ZIP codes, i.e. a six-position zip code (comprising, on average, 20 addresses) for the point of departure and return of around of one quarter of the trips, and a combination of six-position and four-position ZIP codes (consisting of on average 2500 addresses) for the remainder. A maximum of 100 external car and bicycle trips leaving a given municipality were analysed to achieve a manageable amount of work. Denoting N as the number of external trips, every $N/100$th trip was analysed when more than 100 external trips were reported in NTS, as was the case in one third of the municipalities. The average number of external trips in the other two thirds of the municipalities was 60, and only two municipalities had less than 25 external trips in the NTS data set. The result was the average length of the 2008 external car and bicycle trips per municipality, excluding kilometres driven on motorways.

The total amount of car and bicycle use per municipality was calculated by multiplying the average length of the 2008 external trips by the number of external trips in the NTS dataset between 2004 and 2009, and adding to that the total length of the internal trips between 2004 and 2009. Some trips went through more than two municipalities; the part of those trips that fell between different municipalities could not be assigned to a municipality.

2.2. Results

Table 1 presents descriptive statistics of crash victims per crash type (2004–2009), according to age group; Table 2 quantifies annual bicycle and car use per municipality (2004–2009) Note that the annual amount of bicycle and car use for all municipalities together is obtained by multiplying the average use by the number of municipalities and age groups in the dataset.

Table 3 shows the results of the negative binomial regression analyses on recorded victims in car and bicycle crashes in municipalities, 2004–2009. In most cases, the exponent for the growth in crashes in response to the amount of car and bicycle use is significantly lower than 1, indicating that the increase in the number deaths and in-patients in municipalities is proportionally less than the increase in the numbers of kilometres travelled by bicycle and

Table 1
Recorded crash victims per crash type from 2004 up to 2009 in municipalities per age group (minimum and maximum per municipality between brackets).[a]

Age group	Cyclist victims in car crashes						Cyclist victims in other motor vehicle crashes					
	Deaths			In-patients			Deaths			In-patients		
	μ	σ^2	Tot	μ	σ^2	Tot	μ	σ^2	Tot	μ	σ^2	Tot
65+	0.55 (0–6)	0.75	212	4.45 (0–43)	30.59	1724	0.44 (0–5)	0.62	169	1.74 (0–20)	6.02	674
25–64	0.30 (0–9)	0.59	115	8.38 (0–161)	221.18	3242	0.30 (0–8)	0.60	117	3.57 (0–101)	55.21	1382
18–24	0.05 (0–2)	0.05	18	1.73 (0–44)	16.68	670	0.08 (0–4)	0.14	30	0.72 (0–16)	2.62	280
0–17	0.17 (0–4)	0.23	67	4.59 (0–35)	30.02	1775	0.17 (0–3)	0.20	66	1.93 (0–17)	6.31	747
Total	0.27 (0–9)	0.44	412	4.79 (0–161)	80.07	7411	0.25 (0–8)	0.41	382	1.99 (0–101)	18.55	3083

Age group	Car occupant victims in car crashes						Car crash victims in other transport modes than a car (cyclists excluded)					
	Deaths			In-patients			Deaths			In-patients		
	μ	σ^2	Tot	μ	σ^2	Tot	μ	σ^2	Tot	μ	σ^2	Tot
65+	0.73 (0–6)	1.14	282	6.35 (0–48)	39.46	2459						
25–64	1.72 (0–14)	3.93	665	29.95 (0–305)	1240.87	11,591						
18–24	0.97 (0–6)	1.80	377	12.71 (0–113)	164.88	4918						
0–17	0.14 (0–3)	0.20	54	3.09 (0–36)	15.86	1196						
Total	0.89 (0–14)	2.08	1378	13.03 (0–305)	472.07	20,164	0.34 (0–8)	0.52	532	6.52 (0–242)	169.06	10,091

[a] The data set consists of 1548 records for 4 age groups and 387 municipalities.

car. This also applies to cyclist fatalities and in-patients, indicating that as the number of cyclists increases, the risk faced by each cyclist is reduced.

Cyclists older than 65 years of age run an higher risk of being killed or hospitalized than younger cyclists. The fact that the risk of being killed is even more elevated than the risk of being hospitalized is probably due to the fragility of older people. Car occupants run the highest risk of being hospitalized or killed when they are between 18 and 24 years of age, when people are often inexperienced car drivers and susceptible to age-related factors such as peer pressure (SWOV, 2010). The effect of population density differs between victims in different crash types. In highly populated municipalities, fewer cyclists are killed in bicycle–car crashes whereas more people are hospitalized in both bicycle–car and other bicycle–motor vehicle crashes. The risk of car occupants being killed or hospitalized reduces as the population density increases.

The results show that the risks differ significantly between age categories and population density classes. This may impact the effect of a modal shift from short car trips to the bicycle if the exchange is unequally spread amongst these groups. This will be taken into account in the calculations in Section 4 after determining the difference in trip length of the same short trip by car and bicycle.

3. The length of short car trips compared to short bicycle trips

To determine the road safety effect of a modal shift from car trips to cycling, it is necessary to know by how many bicycle kilometres the car kilometres are replaced. It is suggested that bicycle trips are shorter than the car trips they replace (Van Boggelen et al., 2005). To test this hypothesis, we analysed car and bicycle trips in the NTS 2008 shorter than 7.5 km.

3.1. Method and data

Three bicycle trips and three car trips shorter than 7.5 cm were drawn at random from the NTS dataset for half of the municipalities (every two municipalities in the dataset). Only trips with a six-position zip code for the address of departure and return were selected. To determine the difference in distance covered by car versus bicycle for these trips, an approach of drivers' and cyclists' route choice was needed.

For both cyclists and drivers, travel time is the most important factor in route choice. For cyclists, travel time explains route choice slightly better than distance, but the difference is small, due to there being little difference in speeds attained by cyclists on different route options. Around 50% of all cyclists chose a route

Table 2
Amount of bicycle and car use per year per municipality travelled from 2004 up to 2009.[a]

	Bicycle use (10^6 km/year/municipality)		Car use (10^6 km/year/municipality)	
	μ	σ	μ	σ
Age group				
65+	3.18	3.28	11.67	13.51
25–64	17.96	33.90	89.82	125.98
18–24	3.62	6.80	8.72	11.62
0–17	10.07	11.35	15.84	19.63
Total	8.71	19.21	31.51	72.64
Population density class				
High (>742 inh./km^2)	15.18	30.95	50.48	114.03
Medium (272–742 inh./km^2)	6.26	8.10	23.32	38.49
Low (<272 inh./km^2)	4.70	4.66	20.76	28.73
Total	8.71	19.21	31.51	72.64

[a] The data set consists of 1548 records for 4 age groups and 387 municipalities.

Table 3
Estimation results for regression on recorded victims in car and bicycle crashes in municipalities from 2004 up to 2009 (95% Wald CI).

Victim's transport mode	Cyclists		Car occupants				Car crash victims in other transport modes than a car, cyclists excluded	
Crash type	Car crashes		Motor vehicle crashes (except car crashes)		All crash types			
Parameter	Deaths	In-patients	Deaths	In-patients	Deaths	In-patients	Deaths	In-patients
Exponent for growth in crashes in response to								
Amount of bicycle use per age group per municipality	0.26 (0.07–0.45)	0.44 (0.34–0.54)						
Amount of car use per age group per municipality	0.62 (0.41–0.83)	0.55 (0.44–0.67)	0.90 (0.79–1.00)	0.81 (0.75–0.88)				
Amount of car use per municipality					0.73 (0.64–0.82)	0.79 (0.74–0.83)	0.83 (0.72–0.93)	0.92 (0.86–0.99)
Relative risk per age category								
65+	4.15 (3.02–5.70)	1.59 (1.34–1.88)	7.12 (5.46–9.27)	2.24 (1.90–2.65)	6.28 (4.76–8.27)	2.65 (2.37–2.96)		
25–64	1.38 (1.06–1.80)	1.23 (1.08–1.39)	1.00 (0.78–1.29)	1.07 (0.93–1.24)	3.48 (2.59–4.68)	2.43 (2.14–2.77)		
18–24	0.37 (0.23–0.58)	0.50 (0.41–0.60)	1.10 (0.78–1.56)	0.87 (0.72–1.06)	11.02 (8.34–14.55)	6.90 (6.16–7.73)		
0–17 (reference)	1	1	1	1	1	1		
Relative risk per population density class								
High (>742 inh./km²)	0.70 (0.55–0.88)	1.36 (1.21–1.53)	1.01 (0.79–1.28)	1.32 (1.14–1.53)	0.38 (0.32–0.45)	0.64 (0.58–0.71)	0.90 (0.73–1.12)	1.34 (1.18–1.52)
Medium (272–742 inh./km²)	0.89 (0.72–1.11)	1.19 (1.07–1.34)	1.16 (0.92–1.47)	1.05 (0.91–1.21)	0.65 (0.55–0.76)	0.81 (0.74–0.88)	0.94 (0.76–1.16)	1.10 (0.98–1.24)
Low (<272 inh./km²) (reference)	1	1	1	1	1	1	1	1

that deviated less than 5% from the shortest route, with 55% of the actual route overlapping with the shortest route (Aultman-Hall et al., 1997; Gommers and Bovy, 1987). On routes of, on average, 10 min, drivers chose routes that were, on average, 13% slower and longer than the fastest and shortest route (Koning and Bovy, 1980). It is possible that this percentage has decreased due to the use of navigation systems by car drivers, but their use during short routine car trips that are the focus of this study is probably limited. As described in Section 2.2, the route planners of the Dutch Cyclists' Union (Fietsersbond, 2011) and Google Maps (Google, 2011) were used.

3.2. Results

Route analyses were conducted for 1152 trips in 192 municipalities. The length of both car and bicycle trips were compared against each of the three population density classes. Several models were fitted, using curve estimation in SPSS, to predict the length of the fastest route by bicycle with the length of the fastest route by car as the independent variable. A simple linear model without a constant had one of the best model fits (applied to low, medium, and high population density, R^2 was as high as 0.98, 0.97, and 0.95). We selected the linear model form for its good fit and its simplicity as it has only one model parameter. For municipalities with a low, medium, and high population density, the linear regression line has a slope of 0.87 ($t = 111.0$, $p < 0.001$), 0.81 ($t = 114.7$, $p < 0.001$), and 0.77 ($t = 82.8$, $p < 0.001$). These findings are in accordance with the hypothesis formulated by Van Boggelen et al. (2005) that bicycle trips are shorter than short car trips. Also, the results indicate that fewer bicycle kilometres are needed to replace a car trip in high population density municipalities than in those with a low population density.

4. Estimation of the road safety effect of a model shift using the APM method

To estimate the road safety effect of a modal shift from car trips to cycling in Dutch municipalities, the APMs as developed in Section 2 are applied, supplemented with two APMs recently developed for single-bicycle crashes by Schepers (2011). The APMs are estimated for in-patients.

Since 2009, the definition of *in-patient* has been replaced by that for *serious road injury*, the current definition being 'victims admitted into hospital for at least one night, with an injury severity of at least 2 according to the Maximum Abbreviated Injury Score (MAIS)'. The Dutch government has set targets for deaths and serious road injuries. MAIS is an international measure used in medicine to describe injury severity, ranging from 1 (minor) to 6 (fatal). The analyses undertaken in Sections 2 and 3 had to utilize recorded numbers of in-patients and deaths because that was the only measure available at the municipality level. Since the new MAIS-based measure offers, at a national level, a realistic assessment of the number of serious road injuries rather than recorded numbers of in-patients, the road safety effects in this paper are expressed in changes in the number of fatalities and serious road injuries, according to MAIS.

4.1. Mobility data and amount of car and bicycle use in scenarios for a modal shift

Table 4 shows the total annual amount of bicycle and car use (excluding kilometres travelled on motorways) split amongst the four age groups and three population density classes used as input for the APMs to determine the effect of a modal shift. Under Situation 2004–2009, the two columns on the left show the amount of bicycle and car use 2004–2009. The right-hand column shows

Table 4
Amount of bicycle and car use per year travelled from 2004 up to 2009 and in a scenario in which 10% of the amount of car use on short trips replaced by cycling.

Population density	Age	Situation 2004–2009			Scenario: 10% of the amount of car use on short trips replaced by cycling	
		Bicycle use (10^9 km/year)	Car use (10^9 km/year)	Car use for trips up to 7.5 km (10^9 km/year)	Bicycle use (10^9 km/year)	Car use for trips up to 7.5 km (10^9 km/year)
1. High (>742 inh./km^2)	1. 65+	0.61	2.28	0.91	0.68	2.19
	2. 25–64	4.24	18.89	5.65	4.67	18.33
	3. 18–24	0.93	1.73	0.48	0.97	1.69
	4. 0–17	2.05	3.14	1.30	2.15	3.01
	Total	7.83	26.05	8.34	8.47	25.21
2. Medium (272–742 inh./km^2)	1. 65+	0.34	1.12	0.39	0.37	1.08
	2. 25–64	1.55	8.35	2.34	1.74	8.11
	3. 18–24	0.29	0.87	0.23	0.30	0.85
	4. 0–17	1.03	1.60	0.63	1.08	1.54
	Total	3.21	11.94	3.58	3.50	11.58
3. Low (<272 inh./km^2)	1. 65+	0.28	1.11	0.28	0.30	1.08
	2. 25–64	1.16	7.52	1.59	1.30	7.36
	3. 18–24	0.18	0.77	0.15	0.19	0.76
	4. 0–17	0.82	1.39	0.40	0.85	1.35
	Total	2.44	10.79	2.42	2.65	10.55
Total		13.48	48.78	14.33	14.62	47.35

the amount of car use for trips up to 7.5 km (derived from NTS), again broken down in the same age groups and population density classes.

The columns under the heading *Scenario: 10% of the amount of car use on short trips replaced by cycling* show the amount of bicycle use increases with 10% of the amount of car use replaced for trips up to 7.5 km multiplied by 0.87, 0.81, and 0.77 for municipalities with a low, medium, and high population density. Scenarios for other percentages of car kilometres replaced by cycling are calculated in the same way.

4.2. Data on deaths and serious road injuries

To avoid problems of under-reporting in police statistics, our estimations are based on 'real' numbers of fatalities and serious injuries per crash type. Real numbers of fatalities are determined using a combination of data from the National Road Crash Register and Statistics Netherlands' causes of death in the Netherlands. Real number of serious road injuries are acquired by combining data from the National Road Crash Register and the national Medical Registration's hospital data (real numbers are publicly available at the Cognos website of the Dutch Institute for Road Safety Research; SWOV, 2011). Besides real numbers of deaths and serious road injuries, some other characteristics, such as the victim's age and mode of transport, are known, but numbers per crash type are not available and have to be estimated. The mode of transport is sufficient information for car occupant victims; three groups of cyclist victims need to be distinguished: bicycle–car crashes, other bicycle–motor vehicle crashes, and crashes with no motor vehicle involved.

Cyclist crashes with no motor vehicle involved are hardly recorded by the police, even if victims are severely injured. Therefore the National Road Crash Register is of minimal use in distinguishing between cyclists injured in crashes with and without motor vehicles. Causes of Death registration and the National Medical Registration are the only sources suitable to assign the real number of deaths and serious road injuries between cyclist victims who were injured in crashes with and without motor vehicles. These two sources indicate that each year between 2004 and 2009, 40 cyclists were killed (Consumer Safety Institute, 2011) and 7400 seriously injured (Reurings and Bos, 2011) in crashes with no motor vehicle involved. Other cyclist victims were involved in crashes

with motor vehicles, i.e. 149 cyclist deaths and 1555 seriously injured cyclists. Neither source contains other crash information.

Bicycle crashes with motor vehicles are well recorded by the police. Therefore, the number of cyclist victims in other crash types can be estimated by multiplying their share in the National Road Crash Register with the number of victims in motor vehicle crashes according to the other two sources. The numbers of victims in car crashes who are not cyclists or car occupants are determined in the same way. The victim numbers used in this study are shown in the left column of Table 5.

4.3. APM parameters and application

The model parameters from the analyses in Section 2 are used to estimate the road safety effect of a modal shift. Table 5 outlines the APMs' parameter values per crash victim type, supplemented with APMs for bicycle victims in crashes with no motor vehicles involved, according to Schepers (2011). Because of the high level of under-reporting of single-bicycle crashes in police statistics, he used self-reported crash data from surveys additional to police-recorded crash data. These APMs are used to estimate the effect on the number of cyclist victims in crashes with no motor vehicle involved. Besides a model of other victims in car crashes (not car occupants or cyclists), it is theoretically possible to develop a model for other victims (not car occupants or cyclists) in bicycle crashes This has not been done because the number of in-patients and deaths in these crashes is too low to develop a model and, for the same reason, the impact of excluding these crashes is small. The scaling parameters are calibrated to ensure that the predicted victim numbers correspond to the real numbers in the column headed Victims per year (2004–2009) in Table 5.

### 4.4. Modal shift scenarios

The APMs are valid for estimating the effect of a modal shift from short car trips to cycling as far as modal splits of cycling and car driving have actually been realized in the municipalities whose data have been used to develop APMs. In the municipalities with the highest bicycle use such as Groningen and Zwolle, the share of cycling in the modal split is about 50% above the Dutch average, with car driving in the modal split about inversely proportional to cycling (Ministry of Transport, Public Works, and Water Management, 2009). Therefore, the road safety effect of a modal

Table 5

Real numbers of deaths and serious road injuries per year (2004–2009), APM parameters, and estimated road safety effects of a shift to cycling of 10%, 30% and 50% of the amount of car use for short trips up to 7.5 km.

	Victims per year (2004–2009)	α	$\beta1$	$\beta2$	Relative risks RjR_k[a]												Victims per year after a modal shift of short car trips: % of replaced car kilometres on trips up 7.5 km		
					R_1R_1	R_2R_1	R_3R_1	R_4R_1	R_1R_2	R_2R_2	R_3R_2	R_4R_2	R_1R_3	R_2R_3	R_3R_3	R_4R_3	10%	30%	50%
Cyclist fatalities in																			
Bicycle car crashes	77	0.88	0.62	0.26	2.89	0.96	0.26	0.70	3.70	1.23	0.33	0.89	4.15	1.38	0.37	1.00	77	78	77
Other bicycle motor vehicle crashes	72	3.25	0.90		7.15	1.01	1.11	1.01	8.26	1.16	1.28	1.16	7.12	1.00	1.10	1.00	78	89	100
Crashes with no motor vehicle involved[b]	40	1.18	0.52		7.24	2.95	0.86	0.86	8.17	3.33	0.97	0.97	8.42	3.43	1.00	1.00	42	45	49
Car occupants in road crashes	252	3.26	0.73		2.38	1.32	4.17	0.38	4.07	2.26	7.14	0.65	6.28	3.48	11.02	1.00	247	237	227
Other victims in car crashes (cyclists excluded)	101	3.64	0.83		0.90				0.94				1.00				99	94	89
Total	542																542	543	541
Change in deaths per scenario																	0.7	1.1	0.2
Cyclists seriously injured in																			
Bicycle car crashes	1092	14.55	0.55	0.44	2.16	1.67	0.68	1.36	1.89	1.46	0.59	1.19	1.59	1.23	0.50	1.00	1114	1148	1170
Other bicycle motor vehicle crashes	463	27.12	0.81		2.96	1.41	1.15	1.32	2.36	1.12	0.92	1.05	2.24	1.07	0.87	1.00	495	558	620
Crashes with no motor vehicle involved	7400	325.04	0.76		3.92	2.56	1.43	1.43	2.36	1.54	0.86	0.86	2.74	1.79	1.00	1.00	7906	8887	9832
Car occupants in road crashes	2574	37.82	0.79		1.70	1.56	4.43	0.64	2.14	1.96	5.57	0.81	2.65	2.43	6.90	1.00	2518	2405	2291
Other victims in car crashes (cyclists excluded)	2820	59.62	0.92		1.34				1.10				1.00				2742	2586	2430
Total	14,349																14,776	15,585	16,343
Change in serious road injuries per scenario																	427	1236	1994

[a] Relative of j age groups (1. 65+, 2. 25–64, 3. 18–24, 4. 0–17) and k population density classes (1. high, 2. medium, 3. low); The model for other victims in car crashes only contains relative risks for population density classes.

[b] Schepers, 2009; note that cyclist victims between 0 and 24 years of age as a whole were the reference category for age in this study, so the categories 18–24 and 0–17 both have a relative risk of 1.00.
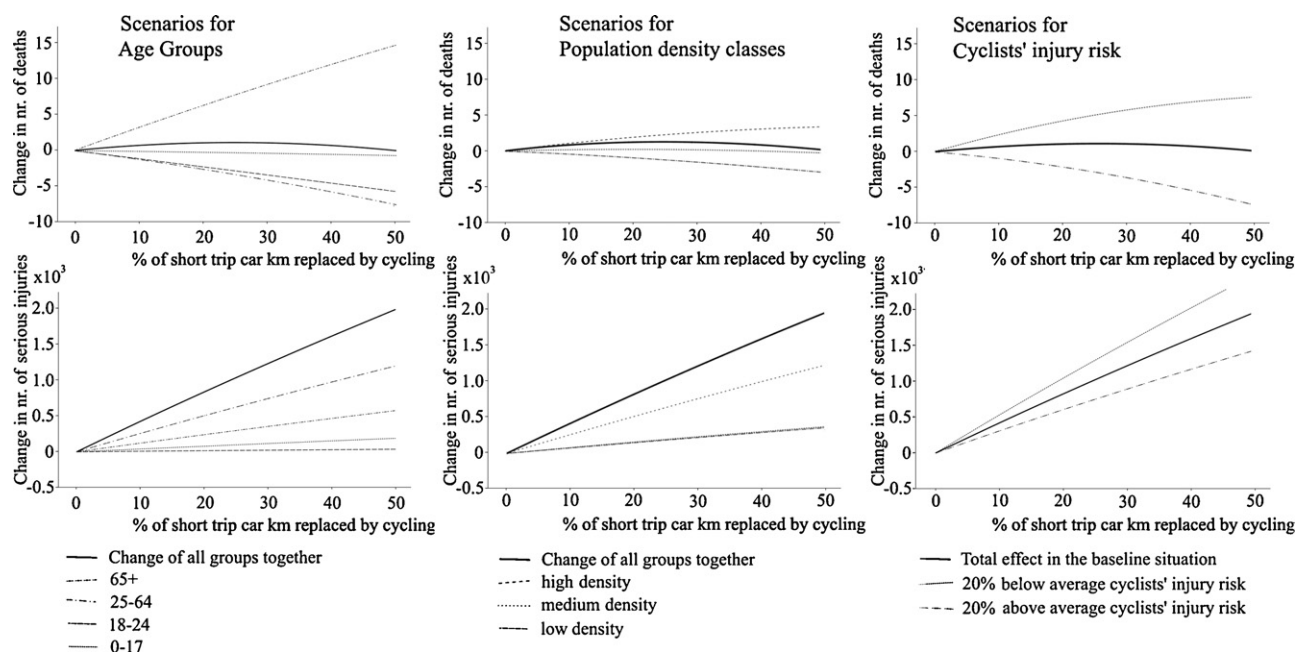
Fig. 1. The effect on the number of deaths (top) and serious injuries (bottom) of an exchange from short car trips to cycling: the contribution of four age groups (left), three density classes (middle), and the effect in scenarios with a 20% lower or higher cyclist injury risk (right).

shift is estimated for scenarios in which the amount of car use on trips up to 7.5 km is halved and replaced by cycling.

As a second step in the scenario analyses, we studied hypothetical scenarios in which the modal shift would be limited to the four age groups or the three population density classes separately. This is done because the road safety effects differ between age groups and municipalities differ in population density. The results show the contribution of groups to the total effect.

As a third step in the analyses we studied the effect on road safety of two scenarios in which municipalities are hypothesized to have a below or above average cyclist injury risk and assuming all else remains the same (for instance car occupant injury risk). This is done because it is conceivable that measures increasing cyclist safety in (both before and after an exchange) also affect the road safety impact of an exchange. As a result, the effect of the modal shift on road safety could improve or worsen compared to the current (baseline) situation on which the APMs are based. This is researched by multiplying the total number of cyclist victims both before and after the exchange by a factor of 0.8 and 1.2, i.e. adjusting the scaling parameter by 20%. These calculations are thus not based on additional calculated APMs. Further, in contrast to the other scenarios that apply to age groups or groups density classes (of which the outcomes sum up to the total effect), the scenarios for cyclists' injury risk apply to all victims together.

4.5. Results: effect estimates for modal shift scenarios

The estimated changes in the number of deaths and serious injuries for modal shifts of 10%, 30% and 50% of the amount of car use for trips up to 7.5 km by cycling are shown in the three right three columns headed *Victims per year after a modal shift of short car trips: % of replaced car kilometres on trips up 7.5 km* in Table 5. The effect on the number of deaths is very small. The rise in the number of cyclists killed in traffic is compensated by a drop in the number of deaths amongst car occupants and other victims in car crashes. The estimates for shifts of 10%, 30% and 50% indicate that the number of serious road injuries increases after an exchange of short car trips for cycling. The main explanation of this result is the high number and corresponding increase of seriously injured cyclist victims in

crashes with no motor vehicle involved. Not including these crash victims in the results would reduce the number of seriously injured victims.

4.5.1. Effect on the number of deaths

The results for deaths are shown graphically in the upper part of Fig. 1. The graphs show the contribution of four age groups (left) and three population density classes (middle) to the total effect, and the effect in scenarios where cyclists would run a 20% lower/higher risk of being injured in an accident (right). From the graphs it can be derived what the effect would have been had the modal shift been limited to a given age group, municipalities in a certain population density class, or municipalities where the point of departure for safety of cyclists compared to drivers is better or worse.

The effect of a modal shift on the number of deaths is strongly negative if only older car occupants exchange car trips for cycling. This can be explained by the relative risks for deaths in Table 3. The relative risk of older cyclists compared to other age groups is more elevated than the relative risk of older car occupants. The result is very positive for the 18–64 age group, and neutral for those aged under 18. Per exchanged car kilometre the gain in safety is greatest for the 18–24 age group, taking into account that many more kilometres are exchanged in the 25–64 age group (see Table 4). The results can be explained by the relative risks noted in Section 2 that are high for young car drivers and not for young cyclists, while the opposite applies to older drivers.

The analyses for population density classes suggest that population density affects the outcome of a modal shift from car trips to cycling only to a small extent. Drivers run a significantly lower risk in high density municipalities as compared to low density municipalities; however this does not apply to the same extent to cyclists. On the other hand, less bicycle kilometres are needed to replace car trips in densely populated municipalities. Therefore, the effect on road safety is only slightly affected by the population density of the municipalities where the exchange takes place.

Finally, a 20% decrease/increase in the chance of cyclists being injured in crashes has a large impact on the effect of a modal shift. A modal shift results in an increase of the total number of deaths if the risk of bicycle injuries increases by 20%, while the total number

of fatalities is estimated to decrease if the risk decreases by 20%. This shows that the effect of a modal shift is likely to be affected by investments in cyclist safety. For instance, bicycle tunnels under busy arteries reduces the exposure to motorized traffic and increases the likelihood that an exchange of car trips for bicycle trips results in a positive road safety effect.

4.5.2. Effect on amount of serious injuries

Our model assessment indicates that the number of serious road injuries will increase in almost all scenarios after a modal shift from driving to cycling. Only where people up to 24 years of age alone exchanged short car trips for cycling is an almost neutral effect likely on the number of serious road injuries. As mentioned before, the increase in injuries results from the rise in the number of cyclist victims in crashes with no motor vehicle involved. Fig. 1 seems to show that the greatest rise in the number of serious road injuries is to be expected in densely populated municipalities. However, the difference mainly results from more kilometres being exchanged in these municipalities as compared to other municipalities. Finally, even if the risk of bicycle injuries decreases by 20% the number of serious road injuries would increase.

5. Discussion

This paper aimed at determining to what extent a shift from short car trips to bicycle trips affects road safety. Cycling is considered a relatively healthy and sustainable mode of transport. However, concerns on road safety represent an important argument against stimulating cycling as cycling is associated with a considerably higher risk of injury accidents and deaths than driving. For determining to what extent this argument is valid, this study focused on the road safety effects in Dutch municipalities using APMs. Elvik (2009) was the first researcher who applied APMs to estimate the effect of a modal shift from car trips to cycling.

The current study is the first one in which APMs are developed using crash and mobility data from municipalities (excluding car kilometres on motorways) and in which the effect of transfers leading to modal spits of car and bicycle use that actually exist in these municipalities is determined. Moreover, this study has included single-bicycle crashes, an important share of all bicycle crashes in the Netherlands and other countries with high amounts of cycling (Veisten et al., 2007; Schepers, 2011). With regard to the number of deaths, the outcome of this study matches the results of the study by Elvik (2009), i.e. transferring a substantial part of trips made by motor vehicles to cycling (or walking) leads to fewer victims. As for the number of serious road injuries, the outcome of this study is clearly more negative than the outcome of Elvik's study (2009), due to the current study also including cyclist victims in crashes with no motor vehicle involved.

The model estimates presented suggest that, under circumstances such as in Dutch municipalities, transferring short trips made by car to cycling has a neutral effect on the number of fatalities and results in an increased number of serious road injuries. The rise in the latter is completely due to the high number of cyclist victims in crashes with no motor vehicle involved, predominantly single-bicycle crashes.

This study is the first with age in the APMs. The effect on the number of deaths of a transfer of car trips up to 7.5 km is neutral, but there are substantial differences between age groups. The number of fatalities above the age of 65 is expected to increase, while that for the 18–64 age group is expected to decrease. Per exchanged car kilometre, the gain is greatest for the 18–24 age group of young drivers. This result is relevant as far as a modal shift would be spread unequally amongst age groups.

6. Recommendations

Road authorities have the opportunity to improve infrastructure safety. To test whether the impact of a modal shift can be influenced by such policies, the effect of a 20% reduction in cyclists' injury risk is estimated. In other words, what would happen if the exchange only took place in municipalities that have reduced cyclist risks by 20% (assuming a constant risk for other transport modes)? The results show that in this scenario, the number of deaths would reduce, due to a modal shift. The number of serious road injuries is still expected to increase, but would be 25% less than would have been the case without the 20% reduction in cyclist injury risk. These results show that research should not be limited to estimating the quantitative effect of more cycling, but should also address the question posed by Wegman et al. (2012): "How to make more cycling good for road safety?"

Governments try to encourage cycling, as it offers benefits to both community and the individual, but concerns about road safety would seem to represent an important argument against this action (Elvik, 2009). This paper showed that a shift from car to bicycle use has little effect on the risk of death. However if more people start cycling, the number of serious injuries is expected to increase, mainly due to single-bicycle crashes. This finding implies that encouraging cycling does not lead to an increase in deaths or car–bicycle accidents, but it does increase the amount of serious road injuries. Given cycling's other advantages such as health benefits (De Hartog et al., 2010), and the fact that additional measures could be taken to reduce the risk of single-bicycle crashes, it may still be worthwhile to encourage a modal shift.

7. Conclusions

Based on this study, the following conclusions can be drawn on the effects of a shift from short car trips to cycling under conditions such as in Dutch municipalities:

- A modal shift has little effect on the number of road deaths.
- However, the number of serious injuries would be expected to increase, mainly due to an increase in single-bicycle crashes.
- Population density affects the outcome of a modal shift only to a small extent.
- There are substantial differences between age groups in the effects of a modal shift. The number of fatalities above the age of 65 is expected to increase, while the number in the 18–64 age group is expected to decrease. Per exchanged car kilometre, the road safety gain is greatest for 18–24 age group of young drivers.

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