Analysis of cyclists' safety on "bicycle streets" in four large Dutch municipalities: A crash and conflict study

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BACKGROUND AND AIM

Starting in the 2000s, a new type of bicycle infrastructure, the *fietsstraat* (bicycle street) emerged, and has been implemented throughout in the Netherlands. A bicycle street is a street on which a minimum of two functions are combined; a flow function for bicycle traffic, and an exchange function for motor vehicle traffic. Therefore on bicycle streets, cyclists are given priority and motorized vehicles are expected to adjust their behavior. This sharing of road space, where motor vehicles are subordinate to bicycles, makes bicycle streets interesting for transportation planners as they are more space efficient. However, mixed traffic conditions are often associated with increased crash risk for non-motorized modes [1]. A handful of studies have addressed the topic of bicycle street safety [2, 3, 4, 5]. Common findings from these conflict and perceived safety studies are that motor vehicle intensities, the road width (incl. rabat strip width), and speed are significant predictors for dangerous encounters and perceived safety. These studies provide a basis for understanding traffic safety on bicycle streets. However, little is known about how the traffic safety on bicycle streets compared with other facilities in terms of crash occurrence and risk for cyclists, and the effects of traffic volumes and design on user behavior and crash rates on bicycle streets. This scarcity of research, in combination with increasing implementation of bicycle streets, is problematic, especially in times of increasing bicycle crash numbers in the Netherlands [6]. The aim of this study is to provide insight into the safety of bicycle streets, using historic crash data as well as the near crash events (i.e., conflicts).

METHODS

The study area consists of the four largest municipalities in the Netherlands, namely Amsterdam, Rotterdam, The Hague, and Utrecht. In addition to being the largest, a high number of bicycle streets is located in these municipalities. The safety evaluation is covered at two levels: 1) a road segment based crash cost rate analysis using historic crash data distinguishing property damage only, light injury, and severe injury/fatal crashes; and 2) a supporting conflict study at selected bicycle streets. Analyzing safety in terms of both crashes and conflicts allows for a more complete understanding of the safety of bicycle streets.

Crash cost rate analysis

First, BRON registered crashes [7] were mapped in GIS and linked to bicycle facility they are located on. Cyclist and vehicle traffic volumes estimated from a traffic model are used to calculate crash cost rate. Then, a model is developed to 1) test the average rates for significant statistical differences, and 2) develop Tobit regression models to quantify the relationships between crash cost rate on different bicycle facilities and various traffic and environmental variables. Two types of regression models were developed: 1) a model for each time period with all bicycle facility links, and 2) separate models for each bicycle facility per time period.

The crash cost rate was estimated for four time periods (average, rush, non-rush, and weekend) based on the sum of observed crash severities, the exposure at the time interval BC_{iT}, the link length L_i, and the relative severity of the crash W_j based on social costs related to the severity level SC_j (Equation 1 and 2) [8].

$$CR_{iT} = \frac{\sum_{n=1}^{j} C_j \times W_j}{y_i \times L_i \times BC_{iT}} \times 10^6 \quad (1)$$

$$W_j = \frac{SC_{fatal}}{SC_j} \times 10^3 \quad (2)$$

Applying conventional models to censored data results in biased and inconsistent parameter estimates. Therefore, the Tobit regression model is used to overcome the zero-inflated data, since it can model segment-based crash data with zero crash segments (i.e. censored at zero), and a crash probability is still modelled [9].
The limited number of bicycle streets leads to an imbalanced dataset for the analysis. Imbalanced datasets suffer from internal model biases where the majority overpowers the minority [10], and it can be difficult to model the effects of the minority classes. To overcome this issue the minority group (bicycle streets) is over-sampled using ADASYN (Adaptive Synthetic Sampling Approach for Imbalanced Learning).

Conflict study
In the second level, a conflict study on a selection of four bicycle streets was performed to support the crash based study, by providing in-depth understanding of how and why crashes on bicycle streets occur. In the conflict study event characteristics (severity, interaction type, road users, evasive action, design) of safe and conflicting interactions are collected on four bicycle streets that vary in traffic volumes and road profile. On each bicycle street video data was collected between 7:00-11:00 and 14:00-19:00 on a weekday, covering both rush and non-rush hours. The interactions were given a severity score following Table 1, where the red line notates the threshold between a safe interaction between road users (above) and a conflict (below).

Table 1 Conflict severity level on bicycle streets [11]

Level	*Overtaking & oncoming traffic*	*Car-behind-bicycle*
1	No hinder of each other, safe situation.	At a comfortable distance.
2	Adjusted behaviour ("make space"), but safe situation.	Close to the cyclist (bothersome).
3	Bothersome (high speed, at small distance), not comfortable, but through adjusted behaviour the probability of a collision is small.	Hard breaking, close to cyclist (dangerous).
4	Very bothersome, breaking or evasive manoeuvre is necessary to prevent collision.	
5	Very dangerous (physical contact), in some cases leading to a crash.	

RESULTS
The two sample z-tests on the average crash cost rates showed that bicycle paths are significantly safer for cyclists than bicycle streets, bicycle lanes, and regular residential roads, on average, and during rush and non-rush hours. This is in line with the general perception that separating bicycle and motor vehicle traffic benefits cyclists' safety. Due to the small bicycle street sample, no significant differences were found between the crash rates during different periods on bicycle streets.
The regression dataset was resampled for the minority class *bicycle street* with majority class *bicycle path*. The neighborhood size (K=20) and balance level (β=0.05) were selected such that changes in variable averages are minimal, and the model performance (significance of coefficients) is optimal. Figure 1 shows the standardized regression coefficients of the four Tobit regression models developed for each time period. The bicycle facility type is modelled as a categorical variable, meaning that each dummy variable is compared with the reference group: bicycle street. Thus, these models show that for each time period the crash cost

rate on bicycle streets is significantly higher than on any other bicycle facility, when controlling for traffic and environmental variables. Motor vehicle volumes are positively related to crash cost rates on bicycle facilities. However, on bicycle streets specifically the findings, both in the crash and conflict part, are unreliable due to data limitations.
On the other hand, both parts produced similar results on the effects of bicycle volumes on crash and conflict rates. Namely, increased bicycle volumes are related to increased crash and conflict rates on bicycle streets. The conflict study also showed that duo-cyclists are exposed to the highest conflict rates, and are strongly disadvantaged on narrow and/or high volume bicycle streets. Also, the results suggest that bicycle streets with very low motor vehicle volumes do not properly facilitate interactions with motor vehicles, as they are primarily designed to facilitate interactions between cyclists.

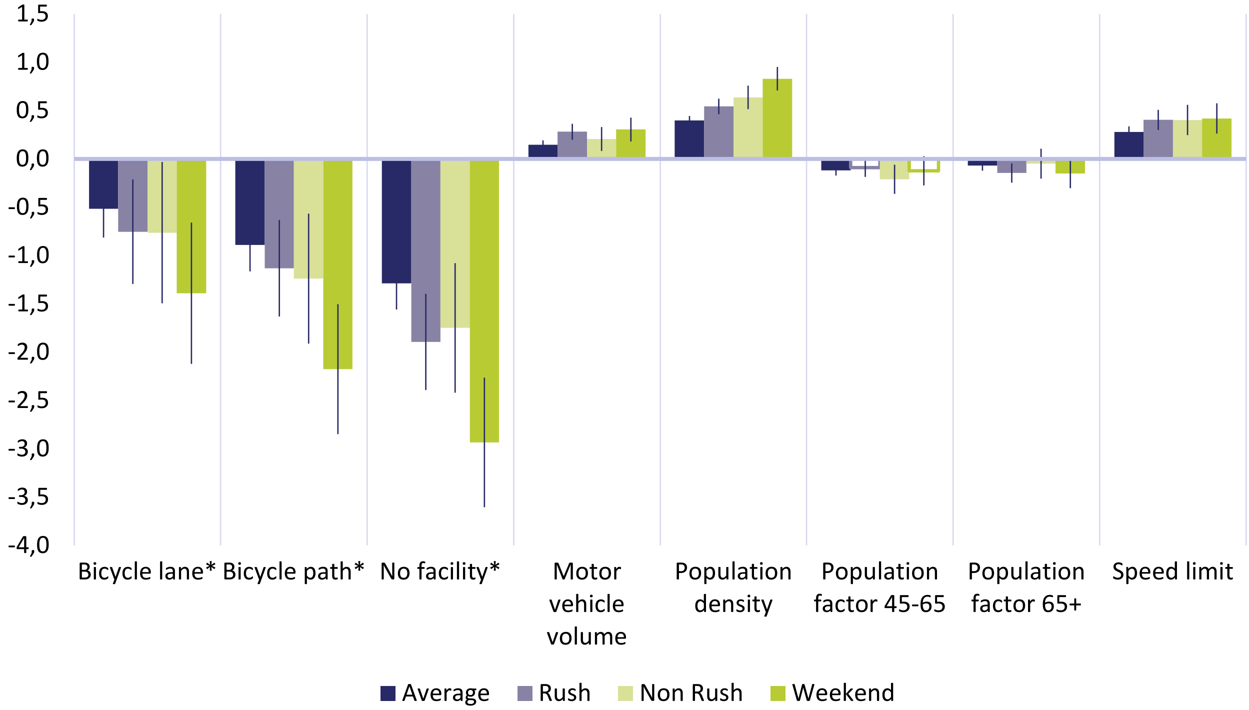

*Figure 1 Standardized regression coefficient of Tobit regression models, for each time period. Error bars show CI at 95%, and significant coefficients p < 0.05 filled bars, *categorical variables are modelled against the reference group: Bicycle street*

CONCLUSIONS
The aim of this study is to provide insight into the safety of bicycle streets, through a comparison of crash cost rates on bicycle streets and other bicycle facilities, and a conflict study on bicycle streets to more specifically address the characteristics of, and related factors to unsafe interactions. The main finding of this study is that crash cost rates for cyclists are higher on bicycle streets than on other bicycle facilities such as lanes and tracks, and on regular residential roads, while controlling for traffic and environmental variables. To conclude, this study adds to the knowledge gap on bicycle street safety by comparing objective safety levels to other bicycle facilities and analyzing the "how" and "why" of unsafe events. It should be noted that these results are subject to some limitations in the crash and traffic volume data. However, the high average crash cost rates, and the regression model outcomes both show lower safety levels on bicycle streets. The conflict study provides characteristics of unsafe events and relationships between traffic volumes and unsafe events are identified. This study provides topics for future directions on bicycle street safety, and takeaways for policy makers and road designers for safer implementation of bicycle streets.

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