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Pedestrian risk decrease with pedestrian flow. A case study based on data from signalized intersections in Hamilton, Ontario

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Abstract

A unique database provided information on pedestrian accidents, intersection geometry and estimates of pedestrian and vehicle flows for the years 1983–1986 for approximately 300 signalized intersections in Hamilton, Ont., Canada. Pedestrian safety at semi-protected schemes, where left-turning vehicles face no opposing traffic but have potential conflicts with pedestrians, were compared with pedestrian safety at normal non-channelized signalized approaches, where right-turning vehicles have potential conflicts with pedestrians. Four different ways of estimating hourly flows for left- and right-turning vehicles were explored. Hourly flows were estimated for periods of 15 min, hours, two periods a day (a.m. and p.m.) and the 'daily' period (7 h). Parameter estimates were somewhat affected by the time period used for flow estimation. However, parameter estimates seem to be affected far more by the traffic pattern (left- or right-turning traffic), even though approaches were selected such that the situation for left- and right-turning turning traffic was similar (no opposing traffic, no advanced green or other separate phases and no channelization). Left-turning vehicles caused higher risks for pedestrians than right-turning vehicles. At low vehicular flows right turns and semi-protected left turns seemed to be equally safe for pedestrians. When risks for pedestrians were calculated as the expected number of reported pedestrian accidents per pedestrian, risk decreased with increasing pedestrian flows and increased with increasing vehicle flow. As risk decreases with increasing pedestrian flows, promoting walking will have a positive effect on pedestrian risk at signalized intersections. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Model; Safety; Pedestrian

1. Background and purpose

The scope of this study was twofold: (a) to explore how safety for pedestrians at conflict with left- and right-turning vehicles is influenced by pedestrian and vehicle flows and (b) to explore how the models are influenced by the choice of different time period for estimating pedestrians and vehicle flows.

The same data base was also used to analyze how typical schemes for accommodating left-turning vehicles influence safety for pedestrians (Quaye et al., 1993).

2. The data

The data gathering part of the project was started by Almuina (1989). His work focused on pedestrian accidents and left-turning vehicles at signalized intersections. As part of his work he prepared an Accident Database and an Intersection Geometry Database for the approximately 300 signalized intersections in the Regional Municipality of Hamilton–Wentworth (Region) in south central Ontario. The majority of the intersections are located in the city of Hamilton in a typical North American grid network with many one-way streets.

To enhance the chances of success of finding a 'pure' relation between pedestrian accidents and pedestrian and vehicle flows, a set of signalized approaches similar in most respects except for traffic flows and accident history were selected. For accidents involving *right-*

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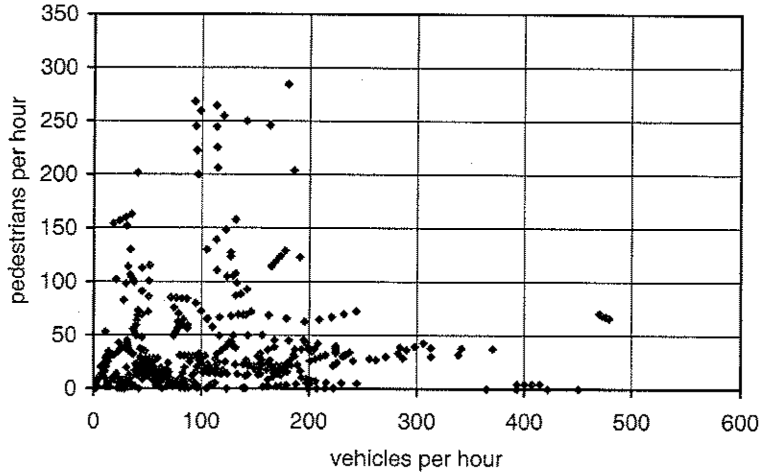

Fig. 1. Pair of flow estimates for the daily model for pedestrians and conflicting left-turning vehicles.

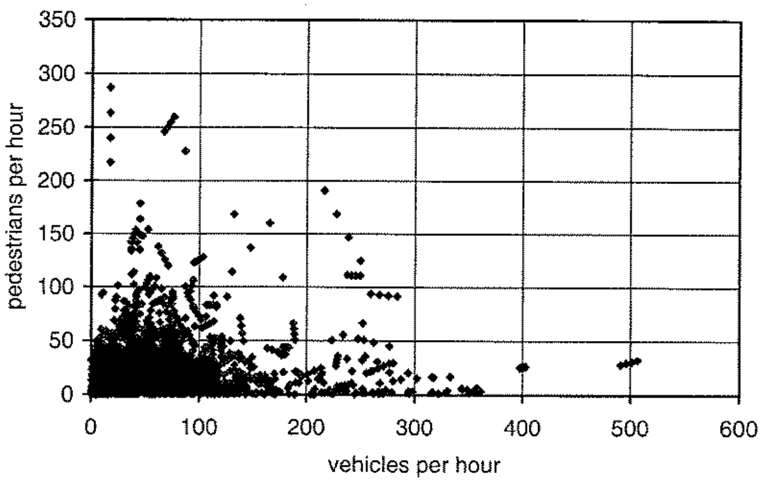

Fig. 2. Pair of flow estimates for the daily model for pedestrians and conflicting right-turning vehicles.

turning vehicles, data were collected for approaches which were not channelized, i.e. where there was no extra island to exclude right-turning traffic from signal control and allow them to yield to pedestrians. Altogether 749 approaches met the criteria for right-turning traffic.

For accidents involving *left-turning* vehicles, the criteria for selecting approaches were: no opposing traffic (so-called *semi-protected scheme*) and no advanced green or other separate phase for left-turning traffic.

Lack of opposing traffic in the approach could be due either to the missing leg in a three-way intersection, or to one-way traffic in the opposite approach leading away from the approach. Altogether 126 approaches met the criteria for left-turning traffic.

The decision as to which approaches fulfilled the criteria was based on information provided in the intersection geometry database and in the microfiches of the intersection layouts. Information about advanced green or other separate phases for left-turning traffic was obtained by interviewing the engineer in charge of the city of Hamilton (Hart Solomon).

The city of Hamilton provided stream counts of vehicles and pedestrians for 15-min periods for 1983–1986. Typically there was one or two counts per year at each intersection. Counts were conducted from 7 to 10 a.m. and from 2 to 6 p.m. Monday–Friday and reported in 15-min periods. From these counts hourly flows were estimated for each 15-min period for all Mondays–Fridays during the study period (Quaye et al., 1993). These estimates were used as a basis for calculating average hourly flows for 15-min, hourly, a.m./p.m. and daily periods of 7 h. Fig. 1 shows pairs of estimates for the daily model of pedestrian flows and conflicting left-turning vehicles (on the cross-walk). Fig. 2 shows pairs of estimates of pedestrian flows and conflicting right-turning vehicles.

As the available accident data were for 1977–1986, flow estimates had to be extrapolated for the years 1977–1982 to correspond to the accident data. However, as these extrapolated estimates did not appear reliable, only the analysis of data from 1983 to 1986 is described here. To correspond to the available traffic count information, accidents should occur between 7 and 10 a.m. and between 2 and 6 p.m. Monday–Friday, and involve left-turning or right-turning vehicles and a pedestrian. Thus 63 accidents from 1977 to 1982 and 66 accidents from 1983 to 1986 remained for the analysis. As noted above, the analysis was restricted to data from 1983 to 1986, leaving a total of 66 accidents, 27 of them between left-turning vehicles and pedestrians and 39 between right-turning vehicles and pedestrians.

3. Method

For models with left-turning vehicles, accidents between pedestrians on the conflicting cross-walk and left-turning vehicles were related to corresponding vehicle and pedestrian flows. For models with right-turning vehicles, accidents between pedestrians on the conflicting cross-walk and right-turning vehicles were also related to corresponding vehicle and pedestrian flows.

1. Average daily flow for each year, *daily model*;
2. Average hourly flows during a.m. and p.m. periods for each year, i.e. 7–10 a.m. and 2–6 p.m. for 1983, 1984 etc., *a.m./p.m. model*;
3. Average hourly flows for each hour and year, i.e. 7–8, 1983, 8–9, 1983, etc., *hourly model* and
4. Average hourly flows for each 15-min period and year, i.e. 7–7:15, 1983, 7:15–7:30, 1983, etc., *15-min model*.

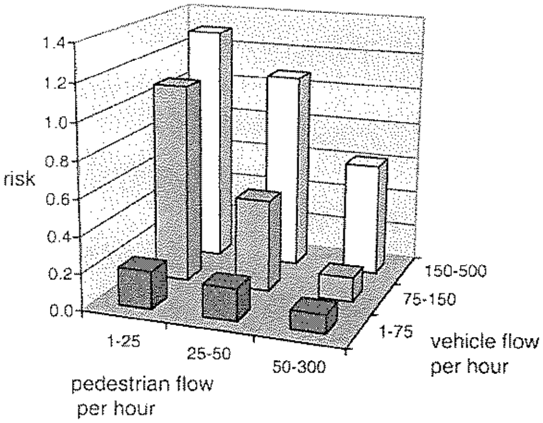

Fig. 3. Pedestrian risks estimated as police-reported accidents per hundred thousand pedestrians for various pedestrian and vehicle flows.

Estimates of average hourly flows were used for a minimum period of 15 min. Flow fluctuates between and within each cycle of a traffic signal system. Flows are systematically higher at the start of the green period. However, the time of the accident related to the start of the green period was not known, therefore it was not possible to study how this influences the safety of a pedestrian.

On the basis of exploratory analysis, one can suggest functional forms for expressions that fit the observations. Experience gained from previous work (Hauer et al., 1989) suggested that it could be reasonable to use the following form of the model:

$$x_i = b_0 F_1^{b_1} F_2^{b_2} + e_i = \hat{E}\{m\} + e_i \tag{1}$$

where for each case i, x_i is the observed number of accidents per unit of time; $\hat{E}\{m\}$ is the estimated number of accidents per unit of time for an 'average' intersection with flow F_1 and F_2; F_1 is the vehicle flow per hour (right-turning or left-turning); F_2 is the pedestrian flow per hour and e_i is the 'error' variable, the residual.

To reduce the effect of random variation the exploratory data analysis was done combining (adding) data for left- and right-turning traffic and calculating pedestrian risks as police reported accidents per hundred thousand pedestrians for various pedestrian and vehicle flows. Fig. 3 suggests that risks are high for pedestrian flows below 25 pedestrians per hour, unless vehicle flows are below 75 vehicles per hour.

The usual approach to the analysis is by multiple regression. To estimate parameters the functions in Eq. (1) were transformed with logarithmic values. The model, expressed in traditional form, can then be written:

$$y_i = \ln x_i = b_0 + b_1 \ln F_1 + b_2 \ln F_2 + e_i = m_i + e_i \tag{2}$$

Coefficients were estimated using the Generalized Linear Interactive Modeling (GLIM) software package (Aitkin et al., 1986) with which it is possible to choose an appropriate error distribution. In order to make the right choice it is necessary to understand the conceptual framework, which is discussed below.

Let the safety of a specific intersection be denoted m_i. Imagine a population of intersections that all have the *same traffic flows*. In this imaginary population, the m_is would still vary from intersection to intersection because, although flows are identical, they involve different drivers in different cities, and so forth. Thus one can speak of the expected value or mean of the ms ($E\{m\}$) in this imaginary population of intersections with *identical* traffic flows. This mean of the ms is what describes the safety of a representative or an 'average' intersection for this imaginary population of intersections with a specific traffic flow. Similarly, one can speak of the variance of the ms.

A model was fitted to accident data, $E\{m\}$ as a function of traffic flow. This describes the m for some 'average' or representative intersection and how it varies with traffic flow. However, the data used for estimation were not for average intersections. Each accident count was for one specific intersection from the imaginary population of intersections with the same flows. It follows that the accident count must be considered as a Poisson random variable originating from a site with $E\{m_i\}$ as its expected value and that this m, in turn, is one of a distribution of ms characterized by $E\{m\}$ and $\mathrm{Var}\{m\}$.

Thus, the distribution of accident counts around the $E\{m\}$ is one family of 'compound Poisson distributions.' In the special case where the distribution of ms in these imaginary populations can be described by a gamma probability density function, the distribution of accident counts around the $E\{m\}$ must be taken as a negative binomial, or in other words the error distribution e_i is a negative binomial (e.g. Leden, 1993).

The variance of accident counts s^2 is given by $\mathrm{Var}\{m\}+E\{m\}$ or

$$\hat{\mathrm{Var}}\{m\}=s^2-x \tag{3}$$

Note that the relationships are not affected by transformation to a logarithmic scale according to Eq. (2). In principle, these relationships can be used to estimate $\mathrm{Var}\{m\}$ for different subsets of the data with almost the same value of $\hat{E}\{m\}$. ($\hat{\mathrm{Var}}\{y_i\}$ can be estimated as $\Sigma e_i^2/n$.) As there was not enough data for this, results from work already done were used (Hauer et al. (1991)). Hauer and Persaud (1987) found that there is often a relationship between $E\{m\}$ and $\mathrm{Var}\{m\}$ and that it can usually be adequately represented by:

$$\mathrm{Var}\{m\}=(E\{m\})^2/k \tag{4}$$

where k is the first parameter of the negative binomial distribution.

This means that the same relationship is valid for subsets of data as for data for the whole Gamma distribution. From Eq. (4) we get for the whole distribution:

$$\mathrm{Var}\{m\}=k/\lambda^2=k^2/(\lambda^2k)=(E\{m\})^2/k$$

Hauer et al. (1991) confirmed the validity of this empirical finding for many groups of their database using Eq. (3).

Two methods can be used to estimate k: the method of moments and the maximum likelihood method. The latter was used. However, some examples calculated by both methods indicate that the two methods give similar results.

Maycock and Maher (1988) and Maher (1989) suggest the method of moments to estimate k. As in Eq. (2), e_i is the residual (y_i-m_i), then

$$E\{e^2\}=m_i+m_i^2/k$$

and an estimate of k is given by:

$$k=\sum\hat{m}_i^2/\sum(e^2-\hat{m}_i) \tag{5}$$

Hauer et al. (1991) describe the maximum likelihood method of estimating k. The iterative process of estimating $\hat{\mathrm{Var}}\{m\}$ begins by estimating provisional model parameters on the assumption that $\hat{\mathrm{Var}}\{m\}=0$ or from some other starting guess. Once we had provisional parameter estimates, a value of k that maximizes the likelihood (L) of the data was estimated as follows: As shown above, the accident counts can be assumed to be distributed as a negative binomial; the parameter a for the negative binomial model can be expressed as a function of k and $E\{m_i\}$ using $E\{m_i\}=b/a$ and $\mathrm{Var}\{m_i\}=b/a^2=(E\{m_i\})^2/k$. Thus the probability of an accident count x_i for case number i can be written:

$$\begin{aligned}p(x_i)&=[a/(a+1)]^k\ [k(k+1)\ldots(k+x_i-1)/x_i!]\\&\quad\times\ [(a+1)^{x_i}]=\\&[k/E\{m_i\}]^k\ [k(k+1)\ldots(k+x_i-1)]\\&\times/[x_i!\ (k/E\{m_i\}+1)^{x_i+k}]\end{aligned}$$

The likelihood function L describes the probability of having the actual outcome of accident counts $x_1,\ldots,x_i,\ldots x_n$. If events are independent this probability can be calculated as $\Pi p(x_i)$. To facilitate calculation, $\ln L$ is calculated instead of L, thus:

$$\begin{aligned}\ln L&=\ln \Pi p(x_i)\\&=k[\Sigma\ln(k/E\{m_i\})]\\&\quad+\Sigma[\ln(k)+\ln(k+1)+\ldots+\ln(k+x_i-1)]\\&\quad-\Sigma(x_i+k)\ln(1+k/E\{m_i\})+\text{constant}^1\end{aligned} \tag{6}$$

Since estimates for $E\{m_i\}$ were provided, it was easy to find the value of k which maximizes $\ln L$ (and L) by calculating $\ln L$ for different values of k. This value of k was then used to calculate $\hat{\mathrm{Var}}\{m\}$ from Eq. (4). The provisional error structure was revised, and model parameters were estimated anew. The process converges in two or three iterations.

As the number of accidents was small, the estimates of k were very uncertain, and in some cases it was not even possible to calculate an estimate of k which maximizes the likelihood. However, the estimates of the model parameters were not very sensitive to changes in k.

Four different ways of estimating hourly pedestrian and conflicting vehicle flows on each cross-walk were explored.

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[1] Not dependent on k.

Table 1
Parameters for estimating expected number of police-reported accidents per day between left-turning vehicles and pedestrians

Flow period	$\hat{b}_0$	$\hat{b}_1$	$\hat{b}_2$	$\hat{k}$
1. Day	2.62×10^{-7}	1.19	0.331	2.2
2. a.m./p.m.	$2 \times 4.85 \times 10^{-8}$	1.37	0.346	*
3. Hour	$7 \times 1.82 \times 10^{-8}$	1.32	0.338	0.4
4. 15 min	$28 \times 3.61 \times 10^{-9}$	1.35	0.368	*

* Insufficient data to estimate k.

Table 2
Parameters for estimating expected number of police-reported accidents per day between right-turning vehicles and pedestrians

Flow period	$\hat{b}_0$	$\hat{b}_1$	$\hat{b}_2$	$\hat{k}$
1. Day	4.19×10^{-7}	0.864	0.475	*
3. a.m./p.m.	$2 \times 1.19 \times 10^{-7}$	0.919	0.570	*
4. Hour	$7 \times 4.08 \times 10^{-8}$	0.913	0.514	*
5. 15 min	$28 \times 2.43 \times 10^{-8}$	0.864	0.321	*

* Insufficient data to estimate k.

4. Results

In all the models estimated, the traffic flows were expressed as vehicles or pedestrians per hour. The dependent variable in each model was based on the number of police-reported accidents occurring in the corresponding time periods[2] (e.g. for the daily model the number of police-reported accidents per day during study hours 7–10 a.m. and 2–6 p.m. was used, etc.). The parameter estimates obtained after fitting the eight models using Eq. (7) and the Generalized Linear Interactive Modeling (GLIM) software package are given in Tables 1 and 2.

$$\hat{E}\{m\} = b_0 F_1^{b_1} F_2^{b_2} \tag{7}$$

where m is the expected number of accidents per unit of time at a certain intersection with an hourly right- or left-turning vehicular flow F_1 and hourly pedestrian flow F_2, $\hat{E}\{m\}$ is the estimated number of accidents per unit of time at a certain intersection and b_0, b_1 and b_2 are parameters to be estimated.

In Fig. 4, the expected number of police-reported pedestrian accidents per day is estimated for a pedestrian flow F_2 of 50 pedestrians per hour for various vehicle flows. Due to the small number of accidents the standard deviation, estimated by the formula $E\{m\}/k^{1/2}$, is relatively great. However it is likely that the expected number of pedestrian accidents per day ($E\{m\}$) is higher for left-turning than for right-turning vehicles (for the specified pedestrian flow).

It should be noted that the estimate from the daily model pertains to information aggregated over two a.m. or p.m. periods, 7 h of the day (specifically: 7–10 a.m. and 2–6 p.m.), or 28 15-min periods. Ideally, one would expect that multiplying the 15-min estimate of $E\{m\}$ by 28, the hourly estimate by seven or the a.m./p.m. estimate by two should yield the daily estimate.

In Figs. 4–7, the curves labeled 1 give the estimates of $E\{m\}$ based on the daily model, for various values of left- or right-turning vehicular flow F_1, while curves 2, 3 and 4 are daily estimates obtained from the a.m./p.m., hourly and 15-min models, respectively, for the same traffic flow combinations.

If risks for pedestrians are calculated as the expected number of reported pedestrian accidents per pedestrian, i.e. Eq. (7) is divided by $7F_2$ (daily pedestrian flow[3]), the risks decrease with increasing pedestrian flow. Fig. 5 shows estimates for $F_1 = 50$ vehicles per hour and Fig. 6 for 500 vehicles per hour. For small vehicle flows ($F_1 = 50$ vehicles per hour), risk differences vanish between left- and right-turning models.

If risks for pedestrians are calculated as the expected number of reported pedestrian accidents per pedestrian, the risks increase with increasing vehicle flow, as seen in Fig. 7.

It is evident from Figs. 4–7 that estimates from the four different models give similar results. Quaye et al. (1993) conclude in their study concerning the effect of semi-protected (where left-turning vehicles face no opposing traffic but conflict with pedestrians) versus permissive schemes (where left-turning vehicles have to find suitable gaps in the opposing traffic) on the safety of pedestrians that it is not statistically incorrect to use any of the three models: 15-min, hourly or daily model, to explore the safety of an intersection over a time period other than that used in its estimation.

5. Summary and discussion

A unique database provided pedestrian accidents and estimates of pedestrian and vehicle flows for the years 1983–1986 for approximately 300 signalized intersections in Hamilton, Ont., Canada. Pedestrian safety at semi-protected schemes, where left-turning vehicles face no opposing traffic but have potential conflicts with pedestrians, were compared with pedestrian safety at normal non-channelized signalized approaches, where right-turning vehicles have potential conflicts with pedestrians.

Four different ways of estimating hourly flows for left- and right-turning vehicles by fitting daily, a.m./

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[2] Each flow estimate corresponds to 5 × 52 periods (one for each weekday of a year).

[3] Seven study hours per day.

p.m., hourly and 15-min models to the data were explored. Parameter estimates were affected by the time period used for flow estimation. However, parameter estimates seem to be affected much more by the traffic pattern (left- or right-turning traffic), even though approaches were selected such that the situation for left- and right-turning traffic was similar (no opposing traffic, no advanced green or other separate phases and no channelization). At low vehicular flows, right turns and semi-protected left turns tend to be equally safe for pedestrians, but right turns are safer for pedestrians than semi-protected left turns (where left turning vehicles have to find suitable gaps in the opposing traffic) at high vehicular flows.

If risks for pedestrians are calculated as the expected number of reported pedestrian accidents per pedestrian, the risk decreases with increasing pedestrian flows. One explanation could be increased driver alertness with increasing pedestrian flow. As the risk decreases with increasing pedestrian flows, promoting walking will

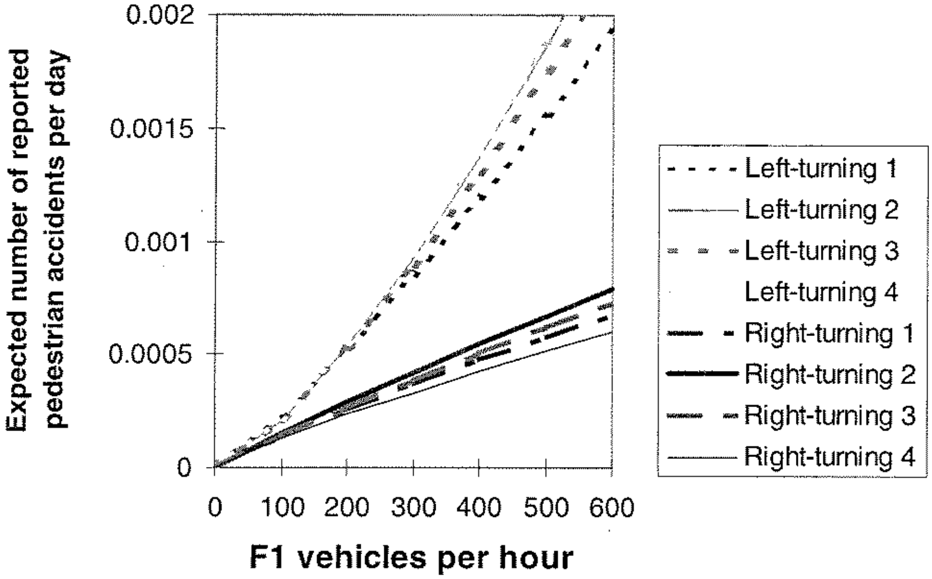

Fig. 4. Estimates of $E\{m\}$ for $F_2 = 50$ pedestrians per hour from the daily (1), a.m./p.m. (2), hourly (3) and 15-min (4) models for left- and right-turning vehicles.

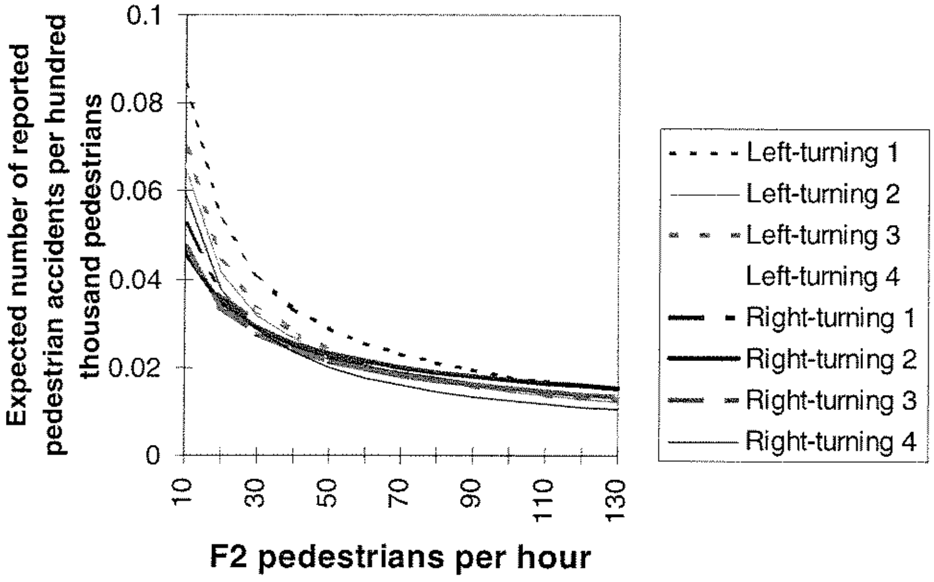

Fig. 5. Estimates of expected number of reported pedestrian accidents per day for $F_1 = 50$ vehicles per hour from daily (1), a.m./p.m. (2), hourly (3) and 15-min (4) models for left- and right-turning vehicles.

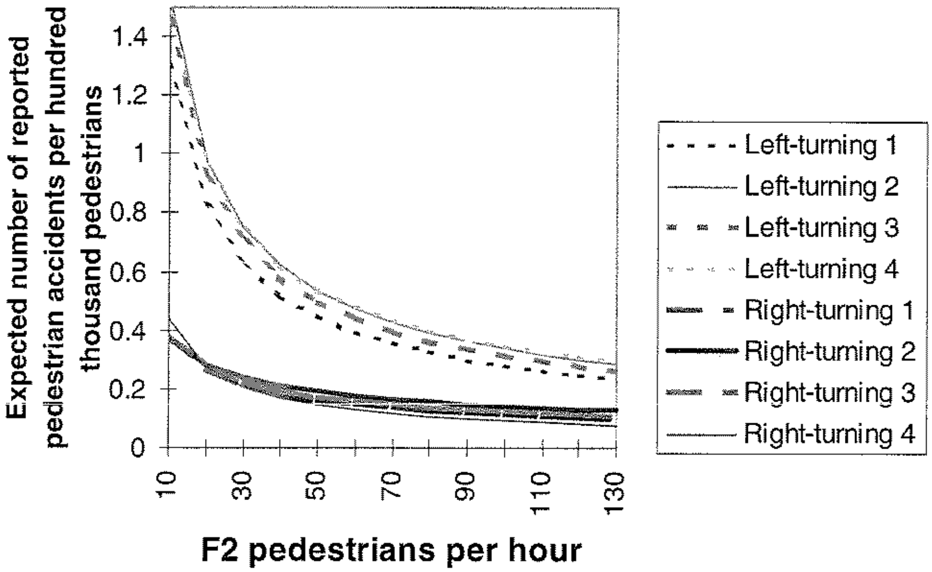

Fig. 6. Estimates of expected number of reported pedestrian accidents per pedestrian for $F_1 = 500$ vehicles per hour from the daily (1), a.m./p.m. (2), hourly (3) and 15-min (4) models for left- and right-turning vehicles.

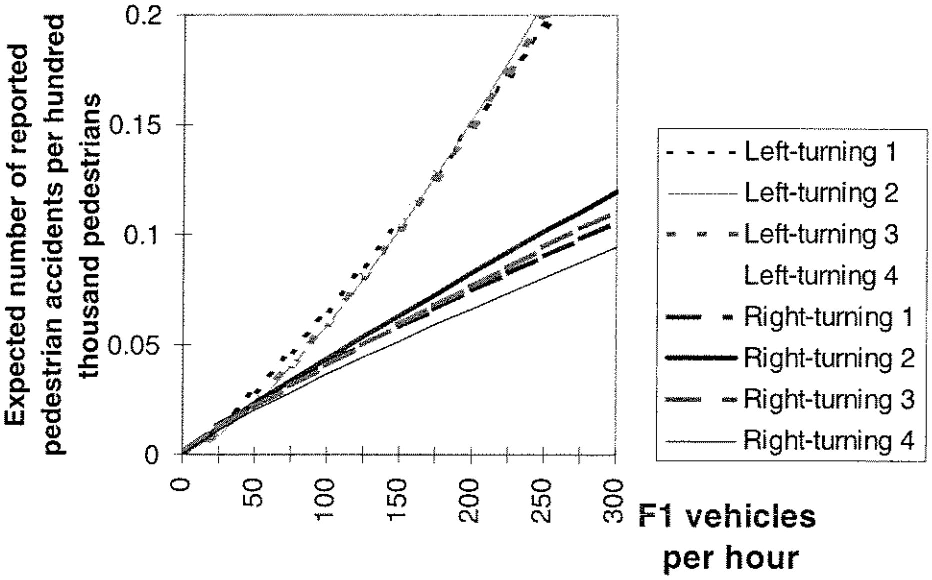

Fig. 7. Estimates of expected number of reported pedestrian accidents per pedestrian for $F_2 = 50$ pedestrians per hour from the daily (1), a.m./p.m. (2), hourly (3) and 15-min (4) models for left- and right-turning vehicles.

have a positive effect on pedestrian risk at signalized intersections. However, an increased pedestrian flow might lead to more pedestrian accidents if promotion is not accompanied by appropriate safety measures, such as speed-reducing devices and increased surveillance of red light running and walking.

Ekman (1996) found for 95 non-signalized intersections in Malmö and Lund in Sweden that the rate of pedestrian conflicts per pedestrian was not influenced by pedestrian flow. According to Ekman this could be interpreted as follows: "The individual pedestrian does not seem to benefit from the presence of other pedestrians. Another interpretation is that the vehicle drivers do expect pedestrians (at least if the pedestrian flow exceeds 30 pedestrians per hour)." Ekman found that the rate of bicycle conflicts per bicyclist decreases with increasing bicycle flow and concluded that the level of bicycle flow is much more important for bicycle risk than the level of car exposure.

Ekman also found (for the 95 non-signalized intersections) that if risks for pedestrians are calculated as the expected number of reported pedestrian accidents or conflicts per pedestrian, the risk increases with increased vehicle flow, i.e. the results are similar to those in Fig. 7.

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