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Effect of street pattern on the severity of crashes involving vulnerable road users

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ABSTRACT

Road crashes not only claim lives and inflict injuries but also create an economic burden to the society due to loss of productivity. Although numerous studies have been conducted to examine a multitude of factors contributing to the frequency and severity of crashes, very few studies have examined the influence of street pattern at a community level. This study examined the effect of different street patterns on crash severity using the City of Calgary as a case study. In this study, street pattern is classified into four categories: grid-iron, warped parallel, loops and lollipops, and mixed patterns. Their effects on injury risk are examined together with other factors including road features, drivers' characteristics, crash characteristics, environmental conditions and vehicle attributes. Pedestrian and bicycle crash data for the years 2003–2005 were utilized to develop a multinomial logit model of crash severity. Our results showed that compared to other street patterns, loops and lollipops design increases the probability of an injury but reduces the probability of fatality and property-damage-only in an event of a crash.

1. Introduction

Road crashes are a leading cause of deaths and injuries in many developed and developing countries. Around the world, about 1.2 million people are killed on the roads each year (WHO, 2004). In Canada, for example, about 3000 road users are killed and 200,000 are injured while traveling on our road networks (Transport Canada, 2004). The province of Alberta alone experiences over 120,000 motor vehicle collisions every year, which result in the deaths of about 400 road users (AIT, 2006). In addition to this staggering number, traffic fatalities have consistently been the leading cause of death for young Albertan (Capital Health, 2007) and Canadian adults (Statistics Canada, 2005).

Among the different road user groups, pedestrians and bicyclists are the most vulnerable and often experience serious injuries due to their lack of protection. Recognizing their vulnerability, many researchers have paid special attention to pedestrian and bicycle involved crashes in order to reduce their frequency and severity (Abdel-Aty et al., 2007; Eluru et al., 2008; Sullivan and Flannagan, 2002; Noland and Quddus, 2004; Macpherson et al., 2004; J.-K. Kim et al., 2007) The injury and fatality risks of these vulnerable road users in traffic crashes are influenced by a multitude of factors, including vehicle characteristics, roadway design characteristics, driver behaviours, types of collisions and environmental conditions. Since evidence-based safety improvements can only be successfully applied if the relevant factors that contribute towards increasing the severity of these crashes are known, many studies have been conducted to identify and quantify the impacts of these contributing factors.

For example, Eluru et al. (2008) found that the general pattern and relative magnitude of elasticity effects of injury severity determinants were similar for pedestrians and bicyclists. Their analysis also suggests that the most important variables influencing non-motorist injury severity are the age of the individual (the elderly are more injury-prone), the speed limit on the roadway (higher speed limits lead to higher injury severity levels), location of crashes (those at signalized intersections are less severe than those elsewhere), and time-of-day (darker periods lead to higher injury severity). In another study, Abdel-Aty et al. (2007) found that the age and gender of the pedestrian or cyclist, proximity to elementary school, number of lanes and speed limit had a significant effect on frequency of crashes involving non-motorists, especially school aged children.

In addition to studies that examined factors contributing to both pedestrian and cyclist crashes, many studies have also been conducted to identify factors contributing to either pedestrian or cyclist crashes. For example, J.-K. Kim et al. (2007) found that greater vehicle speeds prior to impact, truck involved accidents, speeding-involved accidents, intoxicated driver or bicyclist, bicyclist aged 55 and over, inclement weather, darkness without streetlights and head-on collision had a significant effect of the severity of bicycle

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involved crashes. In another study, Lapparent (2005) found that wearing of helmet and the age of cyclist had an impact on the severity of crashes involving cyclists. Also, Macpherson et al. (2004) found that children living outside urban centres had an increased risk of hospitalisation due to bicycling-related injuries.

With respect to pedestrian crash severity, Ivan et al. (2001) found that vehicle type, driver alcohol involvement, pedestrian alcohol involvement, and pedestrian aged over 65 significantly increased the injury severity of pedestrians. Sullivan and Flannagan (2002) found that pedestrian fatalities were three to four times more likely at night than in daylight and seven times higher in unlighted intersections than in lighted intersections. Noland and Quddus (2004) found that more severe pedestrian injuries were associated with areas of lower income population, higher percentage of local roads, higher per capita expenditure on alcohol, and larger numbers of people.

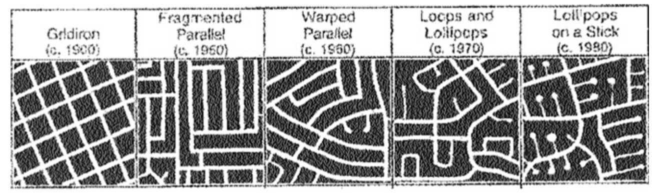
Although the effects of numerous factors have been explored in past studies, little research has been done to explore the effect of street pattern on crash severity. Among the commonly observed street pattern, grid-iron is the more traditional street pattern and is comprised of intersecting streets that are mostly straight thoroughfares. On the other end is the loops and lollipops design which is comprised of roads that are usually curvilinear. This limited access street pattern with loops and cul-de-sacs are often known as the loops and lollipops design. Over the last fifty years, the loops and lollipops design has become the basic building block of many suburban road networks in most North American cities. Although developed to improve the social living environment, this combination of cul-de-sacs and loop streets has the support of many traffic engineers because of its traffic calming effects.

Perhaps due to its intuitive appeal, few studies were conducted to examine the impact of this design on road crashes. In one of the few early studies on street pattern and traffic safety, Marks (1957) found that 50% of all intersections in Los Angeles with the traditional grid pattern had at least one collision whereas only 8.8% of the intersections in limited access pattern had collisions between 1951 and 1956. However, the results of this study have to be interpreted with caution in today's context because it examine only right angled crashes at intersections and ignore all non-intersection crashes. In addition, it does not control for many important influences such as land use and neighbourhood density as well as the economic, social and demographic composition.

In a recent study, Rifaat and Tay (2009) explored the effect of street pattern on the injury risk in two-vehicle crashes using data from the City of Calgary. They classified street pattern or urban form into four categories: grid-iron, warped parallel, loops and lollipops, and mixed patterns. The effects of street pattern on injury risk were examined using a logistic regression model that included control variables like road features, driver characteristics, crash characteristics, environment conditions and vehicle attributes. Their study found that, compared with grid-iron, loops and lollipops type design decreased the injury risk of crashes involving two-vehicle. Although insightful, this study examined only the factors contributing to the injury risk of vehicle–vehicle crashes and not crashes involving vulnerable road users.

In another study, Rifaat et al. (2009) examined the effect of street pattern on the number crashes using similar data from the City of Calgary. They found that currently popular road patterns such as warped parallel, loops and lollipops, and mixed shapes were associated with fewer crashes than traditional gridiron pattern. However, their study examined only total crashes and ignored the severity of crashes. To improve traffic safety, we need to identify and address the factors contributing to both the frequency and severity of crashes.

The above studies are noteworthy because they focused on local roads in general and the street patterns in different community areas in particular. Although most local roads have low traffic volume and speed, our data showed that a little more than half (50.35%) of the total 106,412 crashes occurred on local and collectors roads in Calgary during the period 2003–2005 and the orientation of these local and collector roads might have some influences on community crashes and crash related severities which cannot be ignored from traffic safety perspective. For example, of the 53,574 crashes in the 227 community areas in Calgary, 16.14% have been in community areas with a predominantly gridiron street pattern, 17.21% in warped parallel areas, 53.73% in loops and lollipops areas and 12.92% in areas with mixed street patterns.



(Source: Southworth and Ben-Joseph, 2003)

Fig. 1. Classification of street patterns.

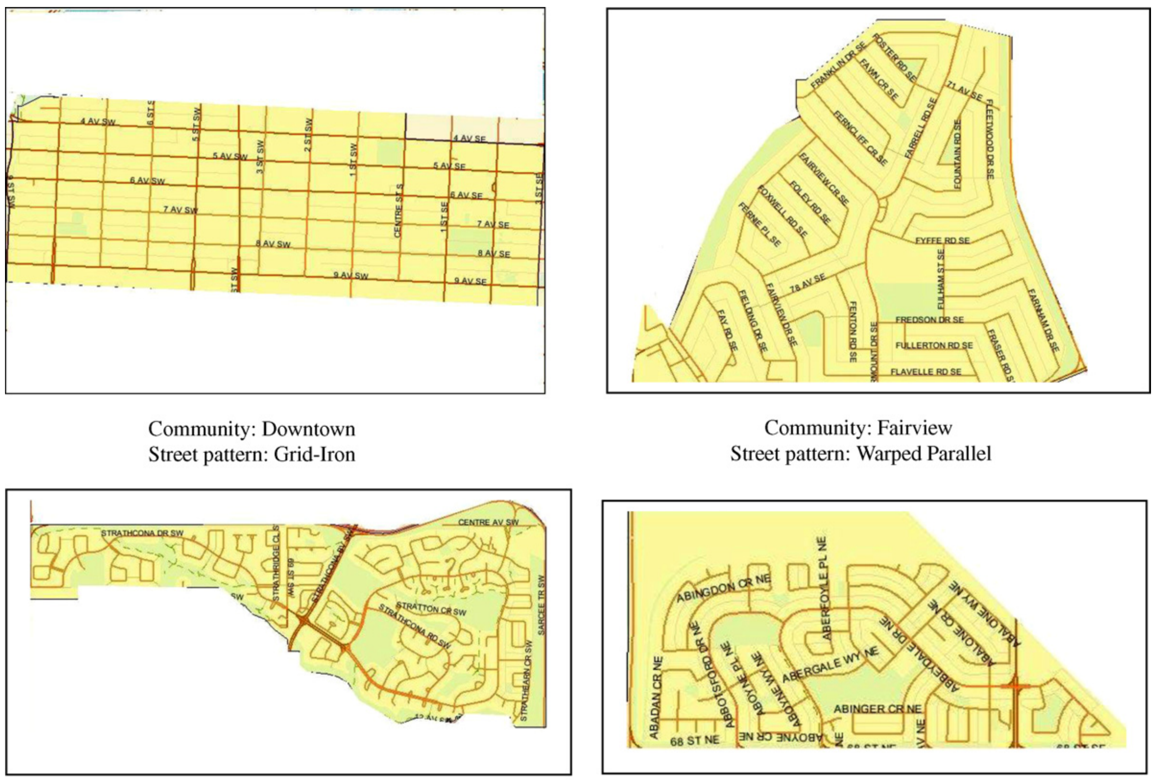
One important issue that has not yet been discussed in the literature regarding the loops and lollipops design is the unintended consequences due to risk compensation behaviour, especially among vulnerable road users. In many modern suburban neighbourhoods, especially in the cul-de-sacs, parents and caregivers are more willing to let children play on the roads (Veitch et al., 2006). This risk compensation behaviour may result in more crashes involving children and since these road users are more vulnerable, these crashes are likely to be more severe. In addition, loops and lollipops designs have horizontal alignment issues and restricted sight distances because of parked vehicles, trees and other roadside furniture. These restrictions may increase the severity of a crash involving pedestrians and cyclists due to shorter stopping distances and higher impact speeds. Therefore, the effect of street pattern on injury risks in a crash is not as certain as some may believed.

Accordingly, the main objective of this study is to understand how different street patterns affect the severity of pedestrian and bicycle involved motor vehicle collisions. Besides street pattern, other factors related to road features, drivers' characteristics, crash characteristics, environmental condition and vehicle attributes are also explored. The City of Calgary is chosen as a case study because this city is growing rapidly due to the economic boom in the oil and gas sector. To accommodate the increased population, the city is expanding laterally and many new communities are being built. Therefore, evidence on the effects of different neighbourhood designs and street patterns on traffic safety is needed to help policy makers, developers and residents make more informed choices.

2. Methodology

2.1. Classifications of street patterns

Since most of the social economic and demographic data were collected from the Canadian Population Census, the community areas defined by the census were used as the basic unit of analysis for street patterns. The street maps of different community areas defined by the Census were extracted from the street directory for the City of Calgary. Based on the street maps, the research team first classified the street pattern of each unit using the classification scheme that was adapted from Southworth and Ben-Joseph (2003). The authors classified street patterns into five categories: grid-iron, fragmented parallel, warped parallel, loops and lollipops, and lollipops on a stick. Their classification is shown in Fig. 1.



Community: Downtown
Street pattern: Grid-Iron

Community: Fairview
Street pattern: Warped Parallel

Community: Strathcona Park
Street pattern: Loops and lollipops

Community: Abbeydale
Street pattern: Mixed

Fig. 2. Examples of road patterns in Calgary.

However, it was found that there were very few community areas with fragmented parallel pattern and this category was merged with grid-iron pattern since it contained mainly straight roadways. Also, the two street patterns with the lollipop designs were merged into one to simplify the classification scheme. Finally, a separate category called mixed pattern was created to allow for community areas with mixed designs. An example of a community in each of the four categories is shown in Fig. 2. Of the 227 community areas, 46 are classified as grid-iron, 55 are warped parallel, 87 are loops and lollipops, and the remaining 39 are mixed pattern. Fig. 3 shows the distribution of the different street patterns in the city. To check that we had classified the units correctly, the procedure was repeated using a sample of 23 transportation engineering students at a local university. The classification produced by the sample matched those produced by the research team.

2.2. Multinomial logit model

For the purpose of this study, the dependent variable is the severity levels of collisions involving pedestrians and cyclists. Since data on the severity of crashes are discrete or categorical in nature, researchers have used a variety of discrete response models. As the severity is also ordinal in nature, many researchers have chosen to use the ordered probit or logit model to study injury severity because these models yield estimates that are consistent and efficient (Pai and Saleh, 2007; Tay and Rifaat, 2007; Rifaat and Chin, 2007; Abdel-Aty and Keller, 2005; Abdel-Aty, 2003; Kockelman and Kweon, 2002; Quddus et al., 2002).

However, some researchers are concerned about the validity of the assumption of a monotonous effect of the independent variables on the dependent variables which is implied in an ordered model. These researchers have chosen instead, to use unordered response models including multilevel binomial logit (D. Kim et al., 2007), multinomial logit (Savolainen and Mannering, 2007; Neyens and Boyle, 2007; Ulfarsson and Mannering, 2004; Lee and Mannering, 2002; Chang and Mannering, 1999; Shankar et al., 1996) and nested logit models (Abdel-Aty et al., 2004; Lee and Mannering, 2002). The multinomial logit model (MNL) is chosen in this study for its increased flexibility in model specification.

The probability of the nth crash having a severity level i, is given by

$$P_{ni} = P(U_{ni} \geq U_{ni'}), \forall i' \in I, i' \neq i \tag{1}$$

where U_{ni} is a function determining the severity, and I is a set of all possible, mutually exclusive severity categories. It is assumed that a road user will experience the injury severity with the largest U_{ni}. If we assume U_{ni} has a linear-in-parameters form, it can be expressed as

$$U_{ni} = \boldsymbol{\beta_i x_n} + \in_{ni} \tag{2}$$

where $\boldsymbol{\beta_i}$ is a vector of coefficients to be estimated for severity outcome i and $\boldsymbol{x_n}$ is a vector of exogenous variables for crashes n. $\in_{ni}$ is the random component (an error term) that explains unobserved influences on injury severity. McFadden (1981) has shown that if $\in_{ni}$ is assumed to have a generalized extreme value distribution, then we have the multinomial logit model which is given by

$$P_{ni} = \frac{e^{\boldsymbol{\beta_i x_n}}}{\sum_{\forall i' \in I} e^{\boldsymbol{\beta_{i'} x_n}}} \tag{3}$$

The coefficients $\boldsymbol{\beta_i}$ can be estimated by the method of maximum likelihood. As the explanatory variables do not vary across injuries and are not injury-specific, the $I-1$ log-odds ratios of the model

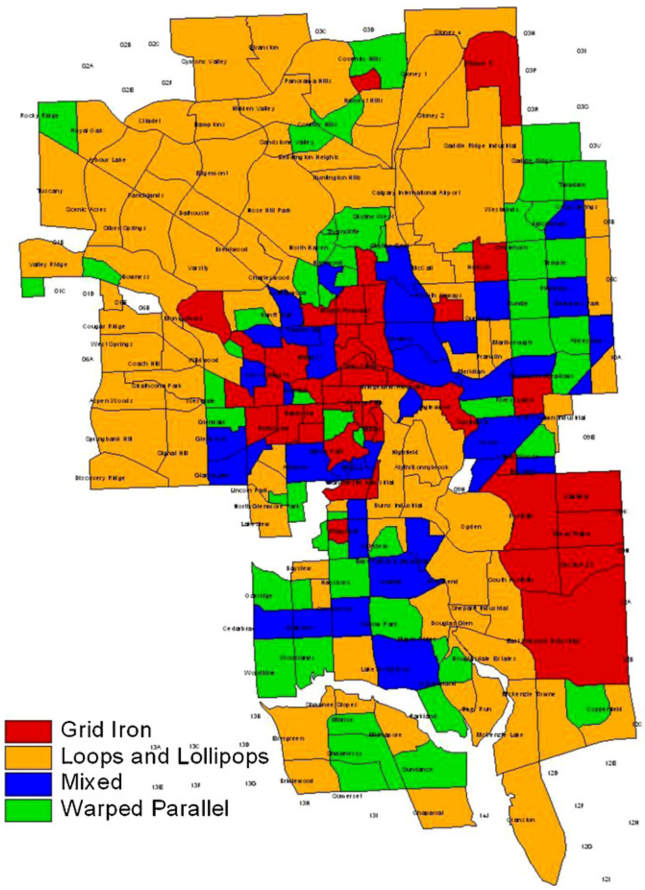


Fig. 3. Distributions of street patterns in Calgary.

outcomes become

$$\ln\left(\frac{P_{ni}}{P_{nI}}\right) = \beta_i' x_n - \beta_I' x_n = (\beta_i' - \beta_I')x_n \quad \text{for } i = 1, \ldots, I-1 \tag{4}$$

Only the difference in coefficients is identifiable and the coefficients are therefore identifiable only up to an additive constant. To resolve this indeterminacy, the coefficients of one outcome (the base case) are set to zero (Greene, 2003). In this study, the non-injury or property damage-only crashes will be used as the base case.

Since the multinomial logit model is a non-linear model, the estimated coefficients of the independent variables do not represent their effects on the dependent variable. One common method used to find the effect of a risk factor is to compute its relative risk ratio (RRR). In this study, since the non-injury crashes are used as the base case, the RRR of a risk factor is computed relative to this case. From Eq. (4), we can see that the relative probability of $i = 2$ (injury crash) to the base outcome (non-injury crash) is

$$\frac{Pr(i=2)}{Pr(i=1)} = e^{\mathbf{X}\beta^{(2)}} \tag{5}$$

Since most of the independent variables are dichotomous variables, the ratio of the relative risk is then given by

$$\text{RRR} = e^{\beta_i^{(2)}} \tag{6}$$

The RRR of an independent variable (for example, loops and lollipops in street pattern) represents the increase in risk (RRR > 1) or decrease in risk (RRR < 1) of a particular severity level (for example, injury or fatal) relative to the case of no injury. In this study, the multinomial logit model and the associated RRR will be estimated by Stata Intercool version 9.0.

Unlike the binary logistic regression model, there are more than two categories in the MNL model. Thus, the effect of a change in a particular variable on one level of severity is a function of its own effect and the effects through the other coefficients in the other injury severity levels (Greene, 2003). Hence, the average direct pseudo elasticity for each independent variable is widely used to quantify the effect of an independent variable on the different injury severity levels (Shankar and Mannering, 1996; Chang and Mannering, 1999; D. Kim et al., 2007). Since most of the independent variables are dichotomous variables, the estimated elasticity of an independent variable gives the average percentage change in probability when the independent variable is changed from zero to one and is given by

$$E_{x_{nk}}^{P_{ni}} = \frac{P_{ni}[\text{given } x_{nk} = 1] - P_{ni}[\text{given } x_{nk} = 0]}{P_{ni}[\text{given } x_{nk} = 0]} \tag{7}$$

The value obtained from the above expression is called the direct pseudo-elasticity which shows the percentage change in probability when the kth indicator variable for vulnerable road user n, x_{nk} is shifted from zero to one or vice-versa. If we insert Eq. (3) into Eq. (7), we will get the brief form of pseudo-elasticity for MNL model:

$$E_{x_{nk}}^{P_{ni}} = \left(e^{\beta_{ik}} \frac{\sum e^{\boldsymbol{\beta}_{i'}\boldsymbol{x}_n}}{\sum e^{\boldsymbol{\Delta}(\boldsymbol{\beta}_{i'}\boldsymbol{x}_n)}}\right) \tag{8}$$

where $E_{x_{nk}}^{P_{ni}}$ is the direct pseudo-elasticity of the kth variable from the vector $\boldsymbol{x}_n$, I is the set of possible outcomes, $\boldsymbol{\Delta}(\boldsymbol{\beta}_i\boldsymbol{x}_n)$ is the value when x_{nk} is set to one and $\boldsymbol{\beta}_i\boldsymbol{x}_n$ is the value with x_{nk} set to zero. The direct pseudo-elasticity for the main policy variables (types of street pattern) will also be computed in addition to the RRR to provide a more complete view of their effects on different severity levels.

2.3. Data

The crash data for this study is provided by Alberta Transportation. Data on crashes involving pedestrians or cyclists for the years 2003–2005 for the City of Calgary are extracted from this provincial database. For simplicity, crashes on roads that form the border between communities were excluded from the study. Of the 2249 pedestrian and bicycle crashes, 1.47% were classified as fatal crashes, 79.55% were classified as injury crashes and the rest were property-damage-only or non-injury crashes.

The severity of a crash is determined by the person with the most severe injury sustained in the crash. In Alberta, a crash is considered as fatal if at least one person dies within 30 days of collision, and it is considered to be an injury crash if at least one person is injured. A property-damage-only (PDO) crash is defined as a crash associated with no injury but only damages to the vehicles or private properties or government property and the damage costs. Note that although all crashes resulting in a cost of over $1000 have to be reported, many minor crashes, especially PDO crashes are not reported.

In theory, the severity of a crash is influenced by various factors related to the road, environment, vehicle and driver. Pre-selection of these factors are accomplished mainly by following previous research where these factors have been explored. However, some local factors, thought to have influence on the severity of crashes, are also examined. Twenty one factors are selected for investigation at the beginning of model development. Since most of the factors were recorded in categories, several dichotomous variables were formed from each factor in order to facilitate the estimation. From the preliminary analyses, 10 factors were found to be insignificant and excluded from the final model which contained 11 factors. Table 1 presents some of the summary statistics and the description of the variables used in the final model.

Table 1
Distribution (%) of crash severity and contributing factors.

Variables (description)	No injury	Injury	Fatality	Total
Street pattern				
Grid-iron	15.04	83.31	1.65	37.05
Warped parallel	19.27	79.73	1.00	18.43
Loops and lollipops	10.58	87.30	2.12	23.15
Mixed	17.77	79.94	2.29	21.37
Road class				
Undivided one-way	18.22	80.84	0.93	13.10
Undivided two-way	15.38	83.05	1.56	50.95
Divided with barrier	13.00	82.67	4.33	16.96
Divided no barrier	9.35	89.72	0.93	6.55
Other/unknown	18.72	80.79	0.49	12.43
Special road location				
No special location	14.96	83.23	1.81	97.86
Private driveway/parking lot	42.11	57.89	0.00	1.16
Interchange ramp	22.22	77.78	0.00	0.55
Other special location (tunnel, underpass, etc.)	28.57	71.43	0.00	0.43
Presence of traffic control device				
None present	16.55	80.76	2.69	43.29
Traffic signal/lights	15.87	83.67	0.45	27.01
Stop sign	15.38	81.54	3.08	3.98
Pedestrian cross walk	11.66	86.81	1.53	19.96
Other control (yield, merge, rail crossing, etc.)	17.02	81.91	1.06	5.76
Seasonal condition				
Fall	15.38	82.39	2.22	35.82
Winter	12.31	86.15	1.54	23.88
Spring	14.73	84.33	0.94	19.53
Summer	19.47	78.47	2.06	20.76
Driver sex				
Male	17.89	80.32	1.79	65.03
Female	10.68	87.57	1.75	34.97
Driver/pedestrian condition				
Normal (no obvious impairment)	14.96	84.09	0.95	76.97
Impaired by alcohol	12.82	79.49	7.69	7.16
Other driver condition (drug, fatigued, etc.)	18.53	78.38	3.09	15.86
Driver age				
Age 0–24	15.49	83.66	0.85	43.48
Age 25–44	17.55	80.32	2.13	34.54
Age 45–69	12.16	85.81	2.03	18.13
Age 70 and above	9.52	82.54	7.94	3.86
Natural lighting condition				
Daylight	16.10	83.38	0.52	70.73
Sun-glare	7.69	92.31	0.00	1.59
Darkness	13.51	81.04	5.45	25.84
Unknown	20.00	80.00	0.00	1.84
Days of week				
Weekends	14.80	83.38	1.81	20.27
Weekdays	15.51	82.72	1.77	79.73
Time of day				
Morning peak	11.83	87.10	1.08	11.39
Midday	15.40	83.84	0.76	40.17
Evening peak	18.88	80.42	0.70	17.51
Evening	14.44	82.94	2.62	23.33
Night-time	15.32	76.61	8.06	7.59

Note: Numbers in second, third and fourth columns are row percentages while those in the last column are column percentages ($N = 1633$).

As shown in Table 1, 37.05% of the collisions occurred in grid-iron community areas while 23.15% occurred in loops and lollipops community areas. Note that warped parallel and mixed street patterns have a relatively larger share of non-injury crashes and a smaller percentage of injury crashes than grid-iron and loops and lollipop designs. Among all the different street patterns, loops and lollipops has the highest share of crashes resulting in injury and the lowest share of crashes resulting in no injury.

Noted that some important factors, such as speed limit, road width, median width, shoulder width, AADT, and pedestrian age and sex, that were identified as having a significant effect on crash severity in previous studies were not examined in this study because of unavailability or missing information. For example, even though AADT data are available for some of the major roadways in the city, they are not available for most local roads within the community. However, an exposure variable such as AADT which captures the traffic volume, is not expected to have a significant effect in our model because the dependent variable is the probability of an injury given that a crash has already occurred (D. Kim et al., 2007). Although exposure is significant in determining the frequency or likelihood of a crash, its impact on crash severity is minimal,

Table 2
Multinomial logit model of injury severity.

Number of observations:	1633
Restricted log-likelihood:	−841.44029
Log-likelihood at convergence:	−780.79978
Chi-square:	90.33
P-value:	<0.001

Variable	Coefficient	Std err	Risk ratio
Injury factors			
Constant***	1.971	0.1410	–
Loops and lollipops***	0.497	0.1741	1.64
Private driveway/parking lot***	−1.271	0.4791	0.28
Winter**	0.358	0.1675	1.43
Male***	−0.569	0.1504	0.57
Other driver conditions*	−0.301	0.1796	0.74
Fatality factors			
Constant***	−2.367	0.4705	–
Divided road with barrier***	2.189	0.4545	8.93
Traffic signal/lights***	−2.554	0.8390	0.08
Impaired by alcohol***	1.542	0.5786	4.67
Other driver conditions*	1.009	0.5307	2.74
Age70 and above***	2.824	0.6172	16.85
Daylight***	−1.992	0.5143	0.14
Weekend**	−1.201	0.5447	0.30
Night-time**	1.277	0.5333	3.58

Note: *, ** and *** denote statistically significant at $\alpha = 0.10$, 0.05 and 0.01. Non-injury crash used as reference or base case.

Table 3
Average direct pseudo-elasticity of variables (% changes).

Variables	No injury	Injury	Fatal
Loops and lollipops	−34.88	7.02	−34.88
Divided road with barrier	−1.69	−1.69	777.59
Private driveway/parking lot	157.32	−27.80	157.33
Traffic signal/lights	0.58	0.58	−92.18
Winter	−26.49	5.17	−26.49
Male	62.83	−7.78	62.83
Impaired by alcohol	−1.02	−1.02	362.55
Other driver conditions	27.78	−5.40	250.33
Age70 and above	−4.26	−4.26	1512.09
Daylight	1.11	1.11	−86.20
Night	−0.73	−0.73	255.81
Weekend	0.28	0.28	−69.82

especially under free flow conditions (D. Kim et al., 2007; Tay, 2009).

Also, while the speed limit of a road is expected to be correlated with its operating speed, its effect on the impact speed of the vehicle involved in a crash, and hence the crash severity, is only indirect. More importantly, the posted speed limit is highly correlated with the types or functional classes of the roads which is included in our study. Quddus et al. (2002) found that type of road and speed limit were strongly correlated and type of road was a better indicator in predicting injury severity than speed limit. From their finding, it is clear that either road type or speed limit is sufficient to reflect the effect of speed on a crash injury.

Note that most of the categorical variables used are self-explanatory. With respect to special road locations, private driveways are places where vehicles enter or exit from the houses/units to the adjacent local roads. They are merged with parking lots in our study because both are associated with very low speed environments and low frequency of crash occurrence. Other special locations include tunnel, underpass, bridges, etc. In terms of traffic control devices, other traffic control devices include yield, merge, railway crossing, etc.

Also, note that two factors relating to time of day and natural lighting condition are somewhat correlated. In the database provided, natural lighting condition is classified into four categories (daylight, sun-glare, darkness and unknown) while occurrence time is provided as continuous variable. The occurrence time has been categorized into the standard morning peak (6:31 a.m.–8:30 a.m.), mid-day (8:31 a.m.–4:00 p.m.), evening peak (4:01 p.m.–6:00 p.m.), evening (6:01 p.m.–12:00 a.m.) and night (12:01 a.m.–6:30 a.m.) to capture qualitative differences in both lighting and traffic conditions. Given the same natural lighting condition, time-of-day will then capture mainly the effects of traffic condition.

3. Results and discussions

The estimation results of the MNL model are presented in Table 2. As discussed earlier, one of the severity categories has to be selected as a base case. In our study, the property-damage-only or no injury case was selected. The results are therefore reported in two categories; one for the likelihood of injury and one for the likelihood of fatality. The estimated coefficients and relative risk ratios (RRR) therefore show the effects of a variable on the likelihood of an injury or fatality respectively. Also, the direct pseudo-elasticity of the statistically significant variables are reported in Table 3 which shows the percentage change in the probability of different injury levels when the indicator variables are changed from 0 to 1. Overall, the model fitted the data fairly well, with a large chi-square statistic and very small *p*-value for the goodness-of-fit. As shown in Table 2, the factors that have a significant effect on the likelihood of an injury are quite different from the factors that have a significant effect on the likelihood of a fatality, indicating that the choice of a multinomial logit model instead of an ordered logit is justified.

3.1. Street patterns

The main objective of our study is to identify the effects of different street patterns on the different levels of injury risks in pedestrian and bicycle involved crashes. The results in Table 2 show that only one of the street patterns has an effect on the severity of crashes involving these vulnerable road users. More specifically, the estimated coefficient for loops and lollipops design on injury risk is positive while its estimated coefficient on fatality risk is not statistically significant and thus omitted from the final model. All the other street patterns are found not to be statistically significant in determining the crash outcomes.

In terms of effect size, the estimated relative risk ratio for the loops and lollipops street pattern under the injury risk model is 1.65. Compared to other street patterns, the risk of suffering a non-fatal injury in the event of a motor vehicle collision is 1.65 times higher than suffering no injury or a fatal injury. In addition to the estimated relative risk ratio, we also computed the direct pseudo-elasticity for different street pattern patterns. Compared with other patterns, the loops and lollipops design shows an inverted U-shaped effect, increasing the probability of injury by 7.02% while decreasing the fatality and no injury by 34.88% (Table 3).

The chances of a fatality in a crash occurring in loops and lollipops neighbourhoods may decrease because of the presence of frequent curves and dead ends which may induce drivers to be more cautious and to reduce their speed. These behaviour adaptations are consistent with the risk compensation theory in economics (Peltzman, 1975; Streff and Geller, 1988; Noland, 1995; McCarthy and Talley, 1999; Tay, 2006) and the risk Homeostasis theory in psychology (Wilde, 1994). In addition, the loops and lollipops street patterns may also have a traffic calming effect on drivers and increase the perception of drivers that it is a residential neighbourhood with an increased likelihood of children at play as well as pedestrians and cyclists on the roads (J.-K. Kim et al., 2007). In summary, it can be explained that lower vehicle speed on these types of roads as a result of driver attentiveness or dead ends in the streets may have contributed to lowering the likelihood of a fatality in the event of a crash.

On the other hand, the presence of frequent curves and loops may restrict drivers' sight distance, resulting in a lower perception and reaction time and hence a lower margin for drivers to reduce their speed before impact which will lead to an increase in the probability of incurring an injury in a crash. In addition, it is possible that parents and caregivers are more willing to let children play in a cul-de-sac or dead end road (Veitch et al., 2006). This risk compensation behaviour may result in more crashes involving children and since these road users are more vulnerable, these crashes may also result in more injuries, even at lower speed.

3.2. Control variables

With respect to roadway and traffic characteristics, our study found that pedestrian and bicycle involved crashes on divided roads with barrier noticeably increased the probability of fatality. This finding was expected because this type of road would be designed for higher speed (Rifaat and Chin, 2007).

The severity of crashes on any kind of special road locations was also examined in our study. It was found that crashes on private driveways or parking lots experienced a lower non-fatal injury risk since these types of crashes would more likely be hit objects (non-injury) or small children (tend to be fatal although very low probability of occurrence). Since most private driveways and parking lots would be designed for lower vehicle speed and many parking lots also had a much lower posted speed limit, most crashes in these areas would have lower impact forces which would result in no injury to vehicle occupants.

The impact of different types of traffic control devices was also explored in our study. Our results indicated that the presence of traffic signals reduced the probability of a fatal injury since it reduced the incidences of side-impact crashes (Short et al., 1982). Also, traffic signals could usually be seen well ahead of the intersections and drivers might be more cautious when approaching the signal. Consequently, drivers might be able to respond quickly and reduce their vehicle speed significantly if needed, thereby resulting in lower crash severity.

Among the environmental factors considered in this study, the effect of seasonal variation on crash severity was found to be significant, with winter season increasing the probability of an injury compared to other seasons, i.e., fall, spring and summer. The unfavourable driving conditions in winter conditions create two effects. Drivers tend to slow down, thereby reducing the likelihood of a fatal crash (Tay, 2009). However, the road surface is covered by snow or ice which increases skidding and braking distance, leading to more injury crashes.

Besides seasonal effects, to capture the effect of visibility, natural lighting conditions (daylight, sun glare, darkness and unknown) are examined. As expected, daylight is found to be negatively correlated with crash fatality. Compared to darkness and sun glare conditions, the vision of drivers and pedestrians/cyclists will not be as hampered during daylight, which will enable them to better detect the other road users, thereby providing them with the time needed to take evasive actions and reduce speed. The effect of the time of crashes is also examined in our study and it is divided into five categories: morning peak, midday, evening, evening peak and night. From the model estimation, it is observed that night-time crashes are more likely to be associated with fatigue, speed and driving under the influence of alcohol which tend to increase fatality risks (Tay et al., 2009).

With regard to road user characteristics, male drivers are found to be associated with lower risks of injury crashes, implying a higher risk of a non-injury or fatal crash. The latter result is probably due to the higher risk taking behaviour of males such as speeding, driving while fatigued, aggressive driving and driving under the influence (Tay, 2005, 2007; O'Brien et al., 2004; Tay and Watson, 2002; Tay et al., 2003). The last influence is reinforced by our previous findings that alcohol impairment is found to increase the risk of fatality in the event of a crash (Ivan et al., 2001; Noland and Quddus, 2004; Harruff et al., 1998). Finally, older drivers are found to be associated with higher fatality risk, a finding that is consistent with the literature (Dellinger et al., 2004; Dulisse, 1997; Evans, 2000; Tay, 2006, 2008).

4. Conclusion

There is constant debate among transportation engineers and urban planners regarding which type of street pattern should be recommended, particularly for new communities and developing communities. In the past, the main purpose of urban streets was to serve as thoroughfares for carrying people and goods from one place to another in a safe and reliable way and with minimum delay. Since the grid-iron street pattern satisfied these requirements very well, it had been the predominant form in many urban areas for a long time (Southworth and Parthasarathy, 1996). However, the Garden City movement at the end of the 19th Century instigated a movement away from the grid toward a new pattern and scale of streets that would improve safety and increase light, air, and the sense of nature in suburban communities (Wolfe, 1987), and over the last fifty years, limited access street patterns had become the predominant street pattern used for developing suburban areas in North America (Southworth and Ben-Joseph, 2003). On the other hand, increasing concerns over social connectivity, physical activities and health, and sustainability of urban transportation had again ignited debate recently on the most appropriate form for urban development (Hess, 2009; Hebbert, 2005).

While the social benefits and drawbacks of different types of street patterns and urban forms have been discussed extensively in the literature (Camagni et al., 2002; Talen, 2006), little attention has been devoted so far to the traffic safety evaluation of these street designs. The main objective of this study is to examine the effect of street patterns on the severity of pedestrian and bicycle crashes using individual crash data and street patterns in different community areas in Calgary. Our study found that relative to grid-iron and other street patterns, the loops and lollipop design was associated with a higher likelihood of non-fatal injury in the event of a collision between a motor vehicle and a pedestrian or cyclist but a lower likelihood of non-injury or fatal injury. The relationship between street pattern and traffic safety for these vulnerable road users is therefore, non-linear and has an inverted U-shape.

From a traffic engineering perspective, this outcome is not surprising since two different factors may play an important role in determining crash severity at both ends. First, the loops and lollipops design tends to have a stronger traffic calming effect. Therefore, the operating speed of vehicles may be lower within the community. If a crash occurs in this situation, it reduces the fatality risk because of less impact force to the bicyclists or pedestrian. On the contrary, the loops and lollipops type of design also reduces sight distances which increases impact speed, which may be significant in enhancing the probability of injury of pedestrians and cyclists. In short, the deviations in speed may be reduced and the impact speed concentrated mainly in the intermediate range.

Besides street pattern, this study also examined a wide variety of control variables relating to road features, environmental conditions, vehicle features, driver attributes and crash characteristics. We found that a crash was likely to be more severe if it occurred on divided roads with barriers, during night time and in times of sun glare or darkness. Older drivers and alcohol impaired drivers or pedestrians would also increase the crash severity. On the other hand, the presence of traffic signals was found to be beneficial in reducing the severity of pedestrian and cyclist involved crashes. In addition, weekend crashes were likely to be less severe than those that occurred on weekdays. Finally, a non-linear effect was observed for some variables including private driveway/parking lot, other impaired driver, male driver and winter season.

Note that this study examined only the effects of different street patterns on the severity of motor vehicle crashes involving a pedestrian or cyclist. Since these road users are especially vulnerable, the results obtained may not reflect the corresponding effect in vehicle–vehicle collisions or vehicle-fixed object collisions. Moreover, it focuses on examining the effect of different street patterns on severity outcomes in the event of a crash, and not on the likelihood of a crash or the frequency of crashes within different types of neighbourhood. Therefore, care should be exercised in interpreting the results with respect to their overall traffic safety effects until more studies on these other effects have been conducted.

References

Abdel-Aty, M., 2003. Analysis of driver injury severity levels at multiple locations using ordered probit models. Journal of Safety Research 34 (5), 597–603.

Abdel-Aty, M., Abdel-Aty, M., Abdel Wahab, H., 2004. Modeling rear-end collisions including the role of driver's visibility and light truck vehicles using a nested logit structure. Accident Analysis and Prevention 36 (3), 447–456.

Abdel-Aty, M., Keller, J., 2005. Exploring the overall and specific crash severity levels at signalized intersections. Accident Analysis and Prevention 37 (3), 417–425.

Abdel-Aty, M., Chundi, S., Lee, C., 2007. Geo-spatial and log-linear analysis of pedestrian and bicyclist crashes involving school-aged children. Journal of Safety Research 38, 571–579.

AIT, 2006. Alberta Traffic Collision Statistics. Alberta Infrastructure and Transportation, Edmonton.

Camagni, R., Gibelli, M., Rigamonti, P., 2002. Urban mobility and urban form: the social, environmental costs of different patterns of urban expansion. Ecological Economics 40 (2), 199–216.

Capital Health, 2007. Protecting new young drivers in Alberta, Capital Health Factsheets, accessed online on 8 June 2010, http:\\www.capitalhealth\safeteendriving.

Chang, L.Y., Mannering, F., 1999. Analysis of injury severity and vehicle occupancy in truck- and non-truck-involved accidents. Accident Analysis and Prevention 31 (5), 579–592.

Dellinger, A., Kresnow, M., White, D., Sehgal, M., 2004. Risk to self versus risk to others: how do older drivers compare to others on the road? American Journal of Preventive Medicine 26 (3), 217–221.

Dulisse, B., 1997. Older drivers and risk to other road users. Accident Analysis and Prevention 29 (5), 573–582.

Eluru, N., Bhat, C., Hensher, D., 2008. A mixed generalized ordered response model for examining pedestrian and bicyclist injury severity level in traffic crashes. Accident Analysis and Prevention 40, 1033–1054.

Evans, L., 2000. Risks older drivers face themselves and threats they pose to other road users. International Journal of Epidemiology 29 (2), 315–322.

Greene, W., 2003. Econometric Analysis, 5th ed. Prentice-Hall.

Harruff, R., Avery, A., Alter-Pandya, A., 1998. Analysis of circumstances and injuries in 217 pedestrian traffic fatalities. Accident Analysis and Prevention 30 (1), 11–20.

Hebbert, M., 2005. Engineering, urbanism and the struggle for street design. Journal of Urban Design 10 (1), 39–59.

Hess, P., 2009. Avenues or arterials: the struggle to change street building practices in Toronto, Canada. Journal of Urban Design 14 (1), 1–28.

Ivan, J., Garder, P., Zajac, S., 2001. Finding Strategies to Improve Pedestrian Safety in Rural Areas. University of Connecticut, Connecticut Transportation Institute, Storrs, CT, 2001.

Kim, J.-K., Kim, S., Ulfarsson, G., Porrello, L., 2007. Bicyclist injury severities in bicycle-motor vehicle accidents. Accident Analysis and Prevention 39, 238–251.

Kim, D., Lee, Y., Washington, S., Choi, K., 2007. Modeling crash outcome probabilities at rural intersections: application of hierarchical binomial logistic models. Accident Analysis and Prevention 39 (1), 125–134.

Kockelman, K., Kweon, Y., 2002. Driver injury severity: an application of ordered probit models. Accident Analysis and Prevention 34 (3), 313–321.

Lapparent, M., 2005. Individual cyclists' probability distributions of severe/fatal crashes in large French urban areas. Accident Analysis and Prevention 37 (6), 1086–1092.

Lee, J., Mannering, F., 2002. Impact of roadside features on the frequency and severity of run-off-roadway accidents: an empirical analysis. Accident Analysis and Prevention 34 (2), 149–161.

Marks, H., 1957. Subdividing for traffic safety. Traffic Quarterly 11 (3), 308–325.

Macpherson, A., To, T., Parkin, P., Moldofsky, B., Wright, J., Chipman, M., Macarthur, C., 2004. Urban/rural variation in children's bicycle-related injuries. Accident Analysis and Prevention 36, 649–654.

McCarthy, P., Talley, W., 1999. Evidence on risk compensation and safety behaviour. Economic Letters 62, 91–96.

McFadden, D., 1981. Econometric models of probabilistic choice. In: Manski, C., McFadden, D. (Eds.), Structural Analysis of Discrete Data with Econometric Applications. The MIT Press, Cambridge, MA.

Neyens, D., Boyle, L., 2007. The effect of distractions on the crash types of teenage drivers. Accident Analysis and Prevention 39 (1), 206–212.

Noland, R., 1995. Perceived risk and modal choice: risk compensation in transportation systems. Accident Analysis and Prevention 27 (4), 503–521.

Noland, R., Quddus, M., 2004. An analyses of pedestrian and bicycle casualties using regional panel data. Transportation Research Record 1897, 23–28.

O'Brien, S., Tay, R., Watson, B., 2004. Situational factors contributing to the expression of aggression on the roads. Journal of the International Association of Traffic and Safety Sciences 28 (1), 101–107.

Pai, C., Saleh, W., 2007. Exploring motorcyclist injury severity resulting from various crash configurations at T-junctions in the United Kingdom—an application of the ordered probit models. Traffic Injury Prevention 8 (1), 62–68.

Peltzman, S., 1975. The effects of automobile safety regulation. Journal of Political Economy 83, 677–726.

Quddus, M., Noland, R., Chin, H., 2002. An analysis of motorcycle injury and vehicle damage severity using ordered probit model. Journal of Safety Research 33, 445–462.

Rifaat, S., Tay, R., Perez, A., de Barros, A., 2009. Effects of neighbourhood street patterns on traffic crash frequency. Journal of Transportation Safety and Security 1 (4), 241–253.

Rifaat, S.M., Tay, R., 2009. Effect of street pattern on injury risks in two-vehicle crashes. Transportation Research Record 2102, 61–67.

Rifaat, S., Chin, H., 2007. Accident severity analysis using ordered probit model. Journal of Advanced Transportation 41 (1), 91–114.

Savolainen, P., Mannering, F., 2007. Probabilistic models of motorcyclists' injury severities in single and multi-vehicle crashes. Accident Analysis and Prevention 39, 955–963.

Shankar, V., Mannering, F., 1996. An exploratory multinomial logit analysis of single-vehicle motorcycle accident severity. Journal of Safety Research 27 (3), 183–194.

Shankar, V., Mannering, F., Barfield, W., 1996. Statistical analysis of accident severity on rural freeways. Accident Analysis and Prevention 28 (3), 391–401.

Short, M., Woelfl, G., Chang, C., 1982. Effects of traffic signal installation on accidents. Accident Analysis and Prevention 14 (2), 135–145.

Southworth, M., Ben-Joseph, E., 2003. Streets and the Shaping of Towns and Cities. Island Press, Washington, DC.

Southworth, M., Parthasarathy, B., 1996. The suburban public realm I: its emergence, growth and transformation in the American metropolis. Journal of Urban Design 1 (3), 245–263.

Statistics Canada, 2005. Leading Causes of Death—Young Adults, accessed online on 8 June 2010, http://www.statisticstop10.com/Causes_of_Death_Young_Adults.html.

Streff, F, Geller, E., 1988. An experimental test of risk compensation: between subject versus within subject analyses. Accident Analysis and Prevention 29 (4), 277–287.

Sullivan, J., Flannagan, M., 2002. The role of ambient light level in fatal crashes: inferences from daylight saving time transitions. Accident Analysis and Prevention 34 (4), 487–498.

Talen, E., 2006. Design for diversity: evaluating the context of socially mixed neighbourhoods. Journal of Urban Design 11 (1), 1–32.

Tay, R., Watson, B., 2002. Changing drivers' intentions and behaviours using fear-based driver fatigue advertising. Health Marketing Quarterly 19 (4), 55–68.

Tay, R., Champness, P., Watson, B., 2003. Personality and speeding: some policy implications. Journal of the International Association of Traffic and Safety Sciences 27 (1), 1–7.

Tay, R., 2005. The effectiveness of enforcement and publicity campaigns on serious crashes involving young male drivers: are drink driving and speeding similar? Accident Analysis and Prevention 37 (5), 922–929.

Tay, R., 2006. Ageing driver: storm in a teacup? Accident Analysis and Prevention 38 (1), 112–121.

Tay, R., Rifaat, S., 2007. Factors contributing to the severity of crashes at intersections. Journal of Advanced Transportation 41 (3), 245–265.

Tay, R., 2007. A comparison of reported driving anger in Canada with USA, UK and Australia. Journal of the Australian College of Road Safety 18 (2), 41–45.

Tay, R., 2008. Marginal effects of increasing ageing driver on injury crashes. Accident Analysis and Prevention 40, 2065–2068.

Tay, R., 2009. Severity of Intersection Crashes in Alberta, Centre for Transportation Engineering and Planning. Edmonton, Alberta.

Tay, R., Barua, U., Kattan, L., 2009. Factors contributing to hit-and-run in fatal crashes. Accident Analysis and Prevention 41 (2), 227–233.

Transport Canada, 2004. Road Safety Vision 2010. Transport Canada, Ottawa.

Ulfarsson, G., Mannering, F., 2004. Differences in male and female injury severities in sport-utility vehicle, minivan, pickup and passenger car accidents. Accident Analysis and Prevention 36, 135–147.

Veitch, J., Bagley, S., Ball, K., Salmon, J., 2006. Where do children usually play? Health and Place 12 (4), 383–393.

WHO, 2004. World Report on Road Traffic Injury Prevention. World Health Organization, Geneva.

Wilde, G., 1994. Target Risk. PDE Publications, Toronto.

Wolfe, C., 1987. Streets regulating neighborhood form: a selective history. In: Moudon, A. (Ed.), Public Streets for Public Use. Columbia University Press, New York.