An Assessment Method of Urban Traffic Crash Severity Considering Traveling Delay and Non-Essential Fuel Consumption of Third Parties

Yi Cao 1, Shiwen Li 1 and Chuanyun Fu 2,*

1 School of Transportation Engineering, Dalian Jiaotong University, Dalian 116028, China; caoyi820619@djtu.edu.cn (Y.C.); lishiwen0129@163.com (S.L.)
2 School of Transportation and Logistics, Southwest Jiaotong University, Chengdu 611756, China
* Correspondence: fuchuanyun@swjtu.edu.cn; Tel.: +86-182-0813-1287

Received: 3 August 2020; Accepted: 19 August 2020; Published: 21 August 2020

Abstract: Urban traffic crashes may lead to only a few casualties, but may generate severe negative impacts on the surrounding traffic, such as evidently increasing traveling delay and non-essential fuel consumption of third parties (i.e., vehicles not involved in the crash). Such detrimental consequences of urban traffic crashes are usually ignored by the traditional crash severity evaluation approaches. Therefore, this study attempts to classify urban traffic crash severity by considering the traveling delay and non-essential fuel consumption of third parties in addition to casualties and property damages. Based on the losses of traveling delay and non-essential fuel consumption of third parties, the losses of crash casualties, and property damages, a comprehensive index of urban traffic crash severity was developed. Moreover, the thresholds of the proposed comprehensive index for urban crash severity classification were determined based on the crash data from 2013 to 2014 collected from Harbin, China. The developed comprehensive index was applied to a case study, which also compared the crash severity classification outcomes from the developed method and the current approach. The results indicate that the developed method of urban traffic crash severity classification is more reasonable than the existing approach. Such superiority of the proposed urban crash severity classification method is due to considering the traveling delay and non-essential fuel consumption of third parties caused by a crash.

Keywords: urban traffic crash; severity level; traveling delay; non-essential fuel consumption; social labor value loss; economic loss of third parties

1. Introduction

Urban traffic crashes result in the massive loss of life and property. According to statistics of the Ministry of Public Security of the People’s Republic of China, there were 244,937 road traffic crashes with casualties in 2018 [1]. Among them, 121,541 traffic crashes occurred on urban roads, accounting for 49.62% of the total crashes. The fatal and injury crashes in the urban setting account for 35.12% and 47% of the total crashes, respectively. Moreover, 34.4% of direct property loss resulted from urban traffic crashes. Additionally, urban traffic crashes usually lead to serious traffic delays and unnecessary fuel consumption, which negatively impact on traffic operation efficiency and energy conservation and environmental protection. Therefore, it is urgent and necessary to evaluate and classify the severity of urban traffic crashes completely and accurately, since it is the basis and premise to conceive reasonable measures to reduce or remove the influences of urban traffic crashes on their surrounding traffic.

In recent decades, the assessment and classification of traffic crash severity are mainly based on the number of casualties, direct economic losses, and indirect economic losses. In practice,
scholars and professionals usually utilize the number of casualties to define the type and severity of a crash [2]. As compared to highway traffic crashes, the number of urban traffic crash casualties is relatively lower. However, urban traffic crashes evidently increase the traveling delay and unnecessary fuel consumption [3]. Moreover, most urban traffic crashes are usually identified as ordinary- or light-severity crashes, if they are assessed by using the traditional criteria of assessment and classification of traffic crash severity. This may lead to an unreasonable crash severity evaluation and classification. Hence, it deserves to explore a novel assessment approach of assessment and classification of urban traffic crash severity by comprehensively considering the delay and economic loss of third parties due to traffic crashes.

Compared with general road traffic, urban road traffic has the characteristics that the traffic density at peak and off-peak hour is greater than that of highway traffic, so special treatment should be taken when evaluating urban road traffic [4,5]. Several studies have been conducted to understand the influence factors of crash severity [6–8]. Different factors that affect crash severity have been investigated, including traffic flow indicators such as traffic volume, speed, heavy vehicle ratio, and other traffic conditions such as traffic density [9], vehicle type, and crash type [10], and environmental factors such as time-of-day and weather [11].

To the estimation of collision severity, Mehmet and N [12] focused on predicting freeway traffic crash severity by employing genetic algorithm (GA), pattern search, and artificial neural network (ANN) approaches. Some studies compared traditional prediction methods, such as Bayesian networks with regression models [13], machine learning, and econometric methods [14], but there are studies that suggested new approaches such as a novel rule-based method to predict traffic crash severity based on user’s preferences [15] and a data mining classification method was applied to identify crash factors and to predict traffic crash severity based on historical crash records [16].

With regard to crash consequence analysis and evaluation, Vorko-Jovic et al. [17] argued that nighttime, urban road section, and speeding are more likely to be associated with fatal crashes. This conclusion was confirmed by a recent study [18,19] that pointed out that the economic loss of a crash includes both direct losses of casualties, damage to vehicles and road facilities, and indirect losses such as traffic delays of other vehicles caused by the crash. Moreover, such indirect losses cannot be ignored. According to the traffic crash record and medical data in Thailand, Riewpaiboon et al. [20] comprehensively analyzed and calculated the direct medical expenses, direct non-medical expenses, indirect mental loss, and productivity loss of a crash. They suggested that the indirect economic loss after considering the mental loss is much higher than the direct economic loss. Based on the non-fatal crash data in Iran, Karimi et al. [21] analyzed the direct and indirect loss of a crash. However, the indirect loss in such a study only considers the delayed work or education cost of the injured persons.

In terms of the assessment of crash consequence, most existing studies mainly focused on casualties and economic losses caused by crashes and overlooked the economic losses of third parties due to crashes. In other words, previous relevant studies do not completely consider the characteristics of fewer casualties but relatively much more serious influences on surrounding traffic operation due to urban crashes. For instance, many urban crashes occurring at peak hour that cause few casualties but lead to serious traffic congestion at the intersections or even on the whole road network are usually treated as light crashes. In addition, it may be not reasonable to assess and classify highway and urban traffic crashes using the same standard. In view of the above-mentioned problems, this study attempts to convert casualties into an economic indicator, and then calculate the economic losses of third parties by considering the traveling delay and the non-essential fuel consumption caused by crashes. After that, a comprehensive assessment model of crash severity is proposed. The contribution of this study is as follows: (i) A delay calculation model under the influence of traffic accidents is established. The model can be used to calculate the total number of vehicles affected by the accident and the average delay of affected vehicles. (ii) By using the delay calculation model parameters, the delay time loss and the value of unnecessary fuel consumption can be calculated, and then they can be included in the economic loss of the third party. (iii) The evaluation model of urban road traffic accident
severity is constructed, and the weight value of each evaluation index is determined. Compared with
the traditional classification method of accident severity, the characteristics of urban traffic accidents
are considered in this study, and the prominent impact of such accidents on surrounding traffic delay
and unnecessary fuel consumption is emphasized. To the best knowledge of the authors, it is the first
time that the indirect economic losses caused by crashes are considered to evaluate and classify crash
severity, and thereby the crash severity assessment and categorization are further improved.

The rest of this study is organized as follows: Section 2 presents the current classification of traffic
crash severity. Section 3 is the model development, including the calculation of a delay caused by
a crash, assessment indexes development, and assessment model. A case study is presented and
discussed in Section 4. The last, Section 5, is the conclusions and limitations of this study, and future
research directions.

2. Current Classification of Traffic Crash Severity

2.1. China

In China, traffic crashes are divided into extremely serious crashes, serious crashes, ordinary
crashes, and light crashes. The crash classification method used in China is relatively simple. In practice,
only the number of deaths and injuries is considered. Additionally, because this classification method
has been adopted since 1992, the conversion problem of the economic indices based on the social
discount rate is not considered. Moreover, in the urban setting, the influence of a traffic crash on
other vehicles is still ignored, such as traffic congestion, traveling delays, and non-essential fuel
consumption. The State Planning Commission stipulated that the social discount rate should be set at
8% (Construction Engineering Standards Manual 2006 Edition) to get the 2018 compensation standard,
as shown in Table 1.

| Crash Classification | Casualty Situation | Original Property Loss (Version 1992) | Converted Property Loss (Version 2018) |
|----------------------|-------------------|--------------------------------------|---------------------------------------|
| Slight crash         | 1 to 2 minor injuries | Less than USD 181 (CNY 1000) for a motorized vehicle crash, or less than USD 36 (CNY 200) for a non-motorized vehicle crash | Less than USD 1118 (CNY 7396) for a motorized vehicle crash, or less than USD 224 (CNY 1479) for a non-motorized vehicle crash |
| Ordinary crash       | 1 to 2 serious injuries or more than 3 minor injuries | Less than USD 544 (CNY 30,000) | Less than USD 33,531 (CNY 221,891) |
| Serious crash        | 1 to 2 deaths or 3 to 10 serious injuries | From USD 544 (CNY 30,000) to USD 1088 (CNY 60,000) | From USD 33,531 (CNY 221,891) to USD 67,063 (CNY 443,781) |
| Extremely serious crash | More than 3 deaths or more than 11 serious injuries or 1 death with more than 8 serious injuries or 2 deaths with more than 5 serious injuries | More than USD 1088 (CNY 60,000) | More than USD 67,063 (CNY 443,781) |

2.2. Some Developed Countries

At present, there are mainly five kinds of classification methods of traffic crash severity widely
used in some developed countries.
(i) The simplest classification. According to injury degree of casualties, traffic crashes are divided into fatal, serious injury, and slight injury crashes. This classification method is still used in Japan;
(ii) The KABCO classification. It is the most widely used classification in the United States, which includes fatal injury (K), incapacitating injury (A), non-incapacitating injury (B), possible injury (C), and property damage only (O) (AASHTO, 2010);
(iii) The abbreviated injury scale (AIS) classification. It was created by the Association for the Advancement of Automotive Medicine and is universally accepted as the foundation of injury severity scaling systems [22]. The AIS level is determined for nine different body regions, which includes minor (1), moderate (2), serious (3), severe (4), critical (5), and unsurvivable (6). The maximum of the AIS scores for each region of the body is called MAIS, which is usually applied to evaluate the overall severity of various injuries;
(iv) The injury severity score (ISS). The ISS is an anatomically based ordinal scale (within a range from 1 to 75) that provides an overall score for patients with multiple injuries [23]. An AIS is assigned to each injury within every single one of six body regions (i.e., head, face, chest, abdomen, extremities (including pelvis), external), and the highest AIS score is used. The highest AIS scores of the three most severely injured body regions are squared and added together to generate the ISS score. The ISS is usually employed to determine the most critical cases;
(v) The new injury severity score (NISS). Unlike the ISS, the NISS is calculated as the simple sum of squares of the three most severe AIS injuries, regardless of body region [23, 24].

3. Model Development

3.1. Calculation of Traveling Delay Caused by a Crash

Once a traffic crash occurs, some lanes are occupied by crash vehicles, and the road capacity reduces as well (see Figure 1). For convenient modeling, the vehicle arrival rate $q$ is assumed to be constant. The departure rate $Q$ of delayed vehicles is assumed to be equal to the total capacity of the road. At this time, the curves of the vehicle arrival rate and departure rate at the crash segment are shown in Figure 2.

\[
\text{Figure 1. Diagram of a traffic crash scene.}
\]

Since the delay time caused by a traffic crash is the area enclosed by the curves of vehicle arrival rate and departure rate, the corresponding delay model can be developed. The evacuation time of queuing vehicles $T_z$ can be calculated by Equation (1):

\[
T_z = \frac{(q - Q_0) \times T_z}{(Q - q)}
\]

where $Q_0$ is the capacity at the bottleneck, after crash vehicles occupying the lane; $T_z$ is the crash duration, which is the time interval from a crash occurring to scene clearing being completed.
Therefore, the total time \( T_m \) and the total number \( N \) of vehicles affected by a crash can be calculated as Equations (2) and (3), respectively:

\[
T_m = T_z + T_2 = \frac{(Q - Q_0) \times T_Z}{(Q - q)} \tag{2}
\]

\[
N = q \times T_m = \frac{(Q - Q_0) \times q \times T_Z}{(Q - q)} \tag{3}
\]

As shown in Figure 2, the total delay of a traffic crash \( S \) is equal to the area of the shaded graph; both \( S_0 \) and \( S_1 \) denote the triangular area; \( S_2 \) represents the trapezoidal area. \( S \) is obtained by the area of the large triangle \( S_0 \) minus the area of the small triangle \( S_1 \) and trapezoid \( S_2 \). They can be calculated by Equations (4)–(8).

\[
S_0 = \frac{1}{2} \times q \times T_m^2 \tag{4}
\]

\[
S_1 = \frac{1}{2} \times Q_0 \times T_z^2 \tag{5}
\]

\[
S_2 = \frac{1}{2} \times (Q_0 \times T_z + q \times T_m) \times (T_m - T_z) \tag{6}
\]

\[
S = S_0 - S_1 - S_2 \tag{7}
\]

\[
S = \frac{(q - Q_0) \times T_Z \times T_m}{2} \tag{8}
\]

The average delay time \( T \) of all vehicles affected by a crash is expressed as Equation (9):

\[
T = \frac{S}{N} + T_0 = \frac{T_Z \times (q - Q_0)}{2 \times q} + T_0 \tag{9}
\]

where, \( T_0 \) is the delay due to the acceleration and deceleration of the affected vehicles during the crash, which is given by Equation (10).

\[
T_0 = \frac{1}{3600} \times \left[ \frac{(v_2 - v_1)}{a_1} + \frac{(v_1 - v_2)}{a_2} + \frac{L}{v_2} - \frac{(L + L_1 + L_2)}{v_1} \right] \tag{10}
\]

where, \( v_1 \) is the interval average speed of the arriving vehicles, m/s; \( v_2 \) is the interval average speed at the bottleneck road segment after crash vehicles occupying a lane, m/s; \( a_1 \) is the average acceleration of vehicles, m/s\(^2\); \( L_1 \) is the maximum queue length of the deceleration interval, m; \( a_2 \) is the average acceleration of vehicles, m/s\(^2\); \( L_2 \) is the maximum queue length of the acceleration interval, m. The first three terms in the right of Equation (10) denote the time of passing three periods under the influence of
a crash, and the fourth term represents the time of passing the same distance without a crash occurrence. The maximum queue length of the congested traffic flow is expressed as Equation (11):

\[ L = \frac{v_f}{2} \times T_Z \]

where \( v_f \) is the wave speed of the vehicles transmitting queuing information, m/s. The traffic wave speed ranges from 0 to \( v_f \). Hence, the average speed of the road section can be assumed to be half of the \( v_f \). According to the theory of traffic wave [25], the traffic wave speed is given by Equation (12).

\[ v_f = \frac{q - Q_0}{q - \frac{Q_0}{v_2}} = \frac{(q - Q_0) \times v_1 \times v_2}{q \times v_2 - Q_0 \times v_1} \] (12)

### 3.2. Assessment Indexes Development

#### 3.2.1. The Loss of Injury

**The Loss of Social Labor Value**

As to the dead people caused by a crash, they no longer produce economic value. Hence, it is necessary to compute the loss (denoted as \( X_{11} \)) of their social labor value. According to the statutory calculation standard of death compensation, it is calculated as Equation (13):

\[
X_{11} = \begin{cases} 
20 \times P_i & \text{if } K \leq 60 \\
\left[20 - (K - 60)\right] \times P_i & \text{if } 60 < K \leq 75 \\
5 \times P_i & \text{if } K \geq 75 
\end{cases}
\] (13)

where \( K \) is the age of dead people; \( P_i \) is the urban per capita disposable income or rural per capita net income at the crash location in the year \( i \).

**The Funeral Expenses**

Based on the statutory calculation standard of the funeral expenses and the standard of the total wage of workers in the last 6 months at the crash location, the funeral expenses can be calculated as Equation (14).

\[ X_{12} = 0.5 \times P_i \] (14)

Therefore, the death loss (\( X_1 \)) caused by a crash is given by Equation (15).

\[ X_1 = n \times (X_{11} + X_{12}) \] (15)

where \( n \) is the number of dead people caused by a crash.

#### 3.2.2. The Direct Economic Loss

Crash injuries include lifelong disabling injury, temporary disabling injury, non-crippling injury, and minor injury [18,19]. In this study, the losses of the social labor value of serious injuries are calculated, since those of minor injury are relatively few.

**Lifelong Disabling Injury**

A person with a lifelong disabling injury cannot work in one year, so his or her total annual social labor value is lost. After treatment, this kind of disabled person has a part of the social labor value after one year. According to the findings of Jiang et al. [26] and Yong et al. [27], the average workability of this kind of person is only equivalent to 55% of full labor. This means that the lost social labor value
due to the lifelong disabling injury accounts for 45% of full labor. Therefore, its corresponding loss is given by Equation (16).

\[
X_{21} = \begin{cases} 
19 \times 45\% \times P_i + P_i & K \leq 60 \\
[19 - (K - 60)] \times 45\% \times P_i + P_i & 60 < K \leq 75 \\
4 \times 45\% \times P_i + P_i & K \geq 75 
\end{cases}
\] (16)

Temporary Disabling Injury

In general, the treatment time for a person with a temporary disabling injury lasts for four to eight months. The duration of 6 months is selected in this study. During this period, they cannot produce the labor value for the community because of the injury [26]. Hence, the loss of temporary disabling injury can be computed as Equation (17).

\[
X_{22} = 0.5 \times P_i
\] (17)

Non-Crippling Injury

A person with non-crippling injury cannot undertake normal work or take part in housework for one month. As such, the loss of a non-crippling injury is given by Equation (18).

\[
X_{23} = \frac{1}{12} \times P_i
\] (18)

Therefore, the social labor value losses of injuries caused by a crash can be expressed as Equation (19):

\[
X_2 = n_1 \times X_{21} + n_2 \times X_{22} + n_3 \times X_{23}
\] (19)

where \(n_1, n_2,\) and \(n_3\) are the numbers of injured persons with different severities involved in a crash.

3.2.3. The Loss of Death

According to Jiang et al. [28] and Zhang et al. [29], the direct economic loss of a crash includes the loss of vehicles, cargoes, and road infrastructures. It can be calculated as Equation (20).

\[
X_3 = X_{31} + X_{32} + X_{33}
\] (20)

where \(X_3\) is the direct economic loss; \(X_{31}\) is the loss of vehicles; \(X_{32}\) is the loss of cargoes; \(X_{33}\) is the loss of road and traffic infrastructures.

3.2.4. The Economic Loss of Third Parties

The Loss of Delay Time

The labor value per unit time can be used to convert the loss of delay time into an economic index [26,27]. The labor value \(p\) per unit time can be estimated according to the urban per capita disposable income \(P_i\) at the crash location for the year \(i\). \(t\) is average daily working hour. For working 250 days per year, the labor value per unit time can be calculated as Equation (21).

\[
p = \frac{P_i}{250 \times t}
\] (21)

Therefore, the increased time value loss \(X_{41}\) caused by a crash can be calculated as Equation (22).

\[
X_{41} = p \times n_4 \times N \times T
\] (22)

where \(n_4\) is the average number of persons within the vehicle affected by a crash.
The Loss of Non-Essential Fuel Consumption

The loss of non-essential fuel consumption caused by a crash is given by Jiang et al. [28] and Zhang et al. [29], as Equation (23) shows.

\[
X_{42} = c \times o \times N \times T \tag{23}
\]

where \(c\) is the average fuel consumption per unit time of every vehicle and is usually set as 0.84 L/h; \(o\) is the average price of gasoline when the crash occurs.

Hence, the economic loss \((X_4)\) of third parties caused by a crash is expressed as Equation (24).

\[
X_4 = X_{41} + X_{42} \tag{24}
\]

3.3. Comprehensive Assessment Method

3.3.1. A Comprehensive Index Construction

The above-mentioned indexes are employed to produce a comprehensive index \((X)\) of the urban traffic crash severity. It is expressed as Equation (25).

\[
X = \ln (\sigma_1 \times X_1 + \sigma_2 \times X_2 + \sigma_3 \times X_3 + \sigma_4 \times X_4) \tag{25}
\]

where \(\sigma_1, \sigma_2, \sigma_3,\) and \(\sigma_4\) are the weights of assessment index \(X_1, X_2, X_3,\) and \(X_4,\) respectively.

Given that the importance of the direct economic loss in the crash is assumed to be equal to that of the indirect economic loss (i.e., economic loss of third parties), by considering the current classification criteria of road traffic crashes (see Table 1), the method of equivalent conversion is utilized to estimate the weighted coefficients of the comprehensive index. For instance, there is an approximate equivalent relationship between one dead person, three seriously injured persons, and an economic loss of USD 22,354. Given that all the dead and wounded persons are younger than 60 years old and the injuries are lifelong disabling injuries, by considering the local per capita disposable income \(P_i\) of urban residents, the weighted coefficients can be obtained: \(\sigma_1 = 0.26, \sigma_2 = 0.18, \sigma_3 = \sigma_4 = 0.28.\)

3.3.2. Assessment Criteria Determination

The crash data from 2013 to 2014 collected from Harbin, China, were applied to obtain a series of values of the comprehensive index of crash severity (see Figure 3). A total of 7532 traffic crashes occurred in the urban road network of Harbin. The information on the number of deaths, serious injuries, minor injuries, direct property loss, crash handling time, and the traffic flow states is used for calculation and evaluation. The percentiles of the comprehensive index are regarded as the thresholds for crash severity classification.

\[\text{Figure 3. Calculation results of the comprehensive index.}\]
The frequency of crashes by the comprehensive index is presented in Figure 4. The values of 85%, 65%, and 30% percentiles of the comprehensive index are chosen to be thresholds. Therefore, the crash severity can be categorized into the following four groups (see Table 2).

![Figure 4. The frequency distribution of crashes by the comprehensive index.](image)

**Table 2. The classification of crash severity by the proposed approach.**

| Crash Severity | Comprehensive Index | Crash Consequence |
|----------------|---------------------|-------------------|
| Grade I        | $X > 9$             | The crash casualties are very serious and lead to very severe traffic congestion. |
| Grade II       | $7 < X < 9$         | The crash casualties are serious and produce severe traffic jams. |
| Grade III      | $5 < X < 7$         | The crash causes a part of economic losses and disturbs the surrounding traffic to some extent. |
| Grade IV       | $X < 5$             | The economic loss caused by the crash is little; there are no serious casualties and serious traffic congestion. |

4. Case Study

4.1. Crash Description

On 25 June 2017, a black Buick sedan car driven by a 65-year-old male driver and collided with a white Toyota car driven by a 36-year-old male driver. This crash happened close to the intersection of Ruanjianyuan Rd and Shuma Rd, Dalian city, China. There were no casualties in such a crash, but it led to traffic congestion and the direct economic loss of USD 962.71. It took half an hour to handle the crash scene. The diagram of the crash scene is shown in Figure 5.
4.2. Calculation of the Assessment Indexes

4.2.1. The Loss of Crash Death and Injury
Since this crash did not cause any casualties, the loss of death and injury is 0. Thus, $X_1 = X_2 = 0$.

4.2.2. The Assessment of Direct Economic Loss
According to the crash description, the direct economic loss is USD 962.71. Hence, $X_3 = 962.71$ USD.

4.2.3. The Assessment of Indirect Economic Loss
Through the actual measurement and description of traffic police, the data are obtained as follows: the vehicle arrival rate $q$ is 2100 pcu/h; the departure rate $Q$ of delayed vehicles after crash treatment is 3600 pcu/h; the capacity $Q_0$ at the bottleneck of the crash scene is 1200 pcu/h. Thus, the total number $N$ of vehicles affected by a crash can be calculated as Equation (26).

$$N = \frac{(3600 - 1200) \times 2100 \times 0.5}{(3600 - 2100)} = 1680 \text{ pcu/h}$$

(26)

The speed of traffic flow was relatively slow, since such a crash occurred during the peak hour. Therefore, there is only a little difference between the average speed $v_1$ of the arriving vehicles and the average speed $v_2$ at the bottleneck road segment. $v_1$ is 9.7 m/s (35 km/h), $v_2$ is 8.3 m/s (30 km/h), $a_1$ is −2.5 m/s², $a_2$ = 1 m/s², $L_1$ = 10 m, and $L_2$ = 20 m. Therefore, the wave speed of the vehicles transmitting queuing information $v_f$, the maximum queue length of the congested traffic flow $L$, and the delay caused by the accelerating and decelerating of the affected vehicles during the accident $T_0$ are calculated as Equation (27) to (29).

$$v_f = \frac{2100 - 1200}{\frac{9.7}{2} - \frac{1200}{8.3}} = 12.51 \text{ m/s}$$

(27)

$$L = \frac{12.51}{2} \times 0.5 = 3.13 \text{ m}$$

(28)

$$T_0 = \frac{1}{3600} \times \left[ \frac{30 - 35}{-2.5} + \frac{35 - 30}{1} + \frac{3.13}{8.3} - \frac{10 + 20 + 3.13}{9.7} \right] = 0.001 \text{ h}$$

(29)

Here, the average delay time $T$ of all vehicles affected by such a crash is calculated as Equation (30).

$$T = \frac{(2100 - 1200) \times 0.5}{2 \times 2100} + 0.001 = 0.108 \text{ h}$$

(30)
According to the statistics, the urban per capita disposable income \( P_i \) at the surroundings in 2017 is USD 6011.29. Working 8 h per day, the labor value per unit time \( p \) can be calculated as Equation (31).

\[
p = \frac{6011.29}{250.8} = 3.01 \text{ USD/h} \quad (31)
\]

Assuming that there were three persons on average in each vehicle affected by the crash, the increased time value loss caused by the crash can be computed as Equation (32).

\[
X_{41} = 3.01 \times 3 \times 1680 \times 0.108 = 1638.40 \text{ USD} \quad (32)
\]

Based on the statistics, the average price of gasoline when the crash occurred was USD 0.99 per liter. Hence, the loss of non-essential fuel consumption caused by this crash can be obtained by Equation (33).

\[
X_{42} = 0.84 \times 0.99 \times 1680 \times 0.108 = 150.89 \text{ USD} \quad (33)
\]

Therefore, the economic loss of third parties due to this crash is calculated as Equation (34).

\[
X_4 = 1638.40 + 150.89 = 1789.29 \text{ USD} \quad (34)
\]

4.3. Assessment of Crash Severity

Based on Equation (25), the comprehensive index \( X \) for the crash severity of this case is obtained by Equation (35).

\[
X = \ln(0 + 0 + 0.28 \times 962.71 + 0.28 \times 1789.29) = 6.65 \quad (35)
\]

According to Table 2, this crash can be identified as a Grade III crash. However, based on Table 1, it is treated as a slight crash. The losses of delay time and non-essential fuel consumption caused by the crash were ignored. Such an issue of previous assessment methods has been completely addressed by the approach proposed in this study.

5. Conclusions

This study developed a comprehensive index of urban traffic crash severity based on the losses of crash casualties, the direct economic loss, and the economic loss of third parties. The economic loss of third parties included the losses of traveling delay and non-essential fuel consumption caused by a crash. According to traffic flow theory, a traveling delay model was proposed to determine the average delay and the total number of vehicles due to a crash. Moreover, the crash data from 2013 to 2014 collected from Harbin, China, were applied to obtain a series of values of the comprehensive index of crash severity. After that, the percentiles of the comprehensive index are regarded as the thresholds for crash severity classification. The developed comprehensive index was used for a case study. The results show that the developed comprehensive index of crash severity can completely deal with the issue that the traditional crash severity classification methods ignore the losses of traveling delay and non-essential fuel consumption caused by traffic crashes. The changes of injury severity, accident duration, and traffic volume will change the final evaluation results. In summary, to the best of the authors’ knowledge, it is the first time a comprehensive index of urban traffic crash severity by considering the losses of traveling delay and non-essential fuel consumption due to traffic crashes has been developed.

However, there are some limitations in this study. Since it is difficult to record an urban traffic crash and collect corresponding traffic flow data, several traffic flow parameters are assumed in the case study. Furthermore, the stale crash data are used to determine the thresholds of the comprehensive index for crash severity classification. Nonetheless, the findings of this study can provide a certain reference for other similar studies. The problem that crash records do not match with corresponding
traffic flow data can be addressed by future studies with advanced data collection technologies, such as big data technology.

**Author Contributions:** Conceptualization, Y.C., S.L. and C.F.; methodology, Y.C., S.L. and C.F.; data curation, Y.C.; investigation, Y.C.; validation, Y.C., S.L. and C.F.; visualization, S.L. and C.F.; writing—review and editing, C.F. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China (Grant No. 11702049; 71801182), LiaoNing Revitalization Talents Program (Grant No. XLYC1807236), Scientific Research Funding Project of Liaoning Provincial Education Department in 2020 and the China Scholarship Council (CSC).

**Acknowledgments:** We appreciate that 7 postgraduates of the university of first author have investigated Conceptualization, Y.C., S.L. and C.F.; methodology, Y.C., S.L. and C.F.; data curation, Y.C.; validation, Y.C., S.L. and C.F.; visualization, S.L. and C.F.; writing—review and editing, C.F. All authors have read and agreed to the published version of the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Li, J.; Wang, Q.; Wang, C. *China Road Traffic Accident Statistics Annual Report; China Ministry of Public Security Traffic Administration*: Wuxi, China, 2019.
2. Lei, W.; Pu, L.V.; Yongjie, L. Traffic accidents on freeways: Influencing factors analysis and injury severity evaluation. *China Saf. Sci. J.* 2016, 26, 86–90. [CrossRef]
3. Khorashadi, A.; Niemeier, D.; Shankar, V.; Mannering, F. Differences in rural and urban driver-injury severities in accidents involving large-trucks: An exploratory analysis. *Accid. Anal. Prev.* 2005, 37, 910–921. [CrossRef]
4. Nowakowska, M. Road traffic accident patterns: A conceptual grouping approach to evaluate crash clusters. *Arch. Transp.* 2012, 24, 73–98. [CrossRef]
5. Ma, Z.; Shao, C.; Dong, C.; Wang, Q. Temporal-spatial analysis model of traffic accident severity based on cumulative logistic model. *China Saf. Sci. J.* 2011, 21, 94–99. [CrossRef]
6. Sun, Y.; Shao, C.; Yue, H.; Zhu, L. Urban traffic accident severity analysis based on sensitivity analysis of support vector machine. *J. Jilin Univ.* 2014, 44, 1315–1320. [CrossRef]
7. Hou, S.; Sun, X.; He, Y.; Tian, Q. Relationships between crash severity and traffic flow characteristics on freeways. *China Saf. Sci. J.* 2011, 21, 106–112. [CrossRef]
8. George, Y.; Athanasios, T.; George, P. Investigation of road accident severity per vehicle type. *Transp. Res. Procedia* 2017, 25, 2081–2088. [CrossRef]
9. Feng, Z.; Lei, Y.; Zhang, W.; Wang, K.; Han, S. Analysis on traffic accident severity influenced by road environment on circular highway. *China J. Highw. Trans.* 2016, 29, 116–123. [CrossRef]
10. Kunt, M.M.; Noii, N. Prediction for traffic accident severity: Comparing the artificial neural network, genetic algorithm, combined genetic algorithm and pattern search methods. *Transport* 2011, 26, 353–366. [CrossRef]
11. Zong, F.; Xu, H.; Zhang, H. Prediction for traffic accident severity: Comparing the bayesian network and regression models. *Math. Probl. Eng.* 2013, 12, 475194.1–475194.9. [CrossRef]
12. Galatioso, F.; Catalano, G.; Shaikh, N.; McCormick, E.; Johnston, R. Advanced accident prediction models and impacts assessment. *IET Intell. Transp. Syst.* 2018, 12, 1131–1141. [CrossRef]
13. Hashmiejad, S.H.A.; Hasheminejad, S.M.O. Traffic accident severity prediction using a novel multi-objective genetic algorithm. *Int. J. Crashworth.* 2017, 22, 1–16. [CrossRef]
14. Hong, T.P.; Tran, V.L.; Van, H.T. Immediate Velocity Prediction of a Mixed-Traffic Flow in Urban Road Networks with Spatial-Temporal Correlation Analysis. In Proceedings of the International Conference on Green Technology and Sustainable Development, Ho Chi Minh City, Vietnam, 23–24 November 2018. [CrossRef]
15. Abtahi, S.M.; Haghshenash, H. Analysis and modeling time headway distributions under heavy traffic flow conditions in the urban highways: Case of Isfahan. *Transport* 2011, 26, 375–382. [CrossRef]
16. Bahiru, T.K.; Kumarsingh, D.; Tessfaw, E.A. Comparative Study on Data Mining Classification Algorithms for Predicting Road Traffic Accident Severity. In Proceedings of the International Conference on Inventive Communication and Computational Technologies, Coimbatore, India, 20–21 April 2018. [CrossRef]
17. Vorko-Jovic, A.; Kern, J.; Biloglav, Z. Risk factors in urban road traffic accidents. *J. Saf. Res.* 2006, 37, 93–98. [CrossRef]
18. Verzosa, N.; Mile, R. Severity of road crashes involving pedestrians in Metro Manila, Philippines. *Accid. Anal. Prev.* 2016, 94, 216–226. [CrossRef]

19. Yin, S.; Chen, X.; Li, M.; Shi, Q. Evaluation of accident-induced indirect costs for measuring penalties on violations of laws. *Transp. Res. Rec.* 2012, 2371, 111–120. [CrossRef]

20. Riewpaiboon, A.; Piyanuch, P.; Chaikledkaew, U. Economic burden of road traffic injuries: A micro-costing approach. *Southeast Asian J. Trop. Med. Public Health* 2008, 39, 1139–1149.

21. Karimi, H.; Soleyman-Jahi, S.; Hafezi-Nejad, N. Direct and indirect costs of nonfatal road traffic injuries in Iran: A population-based study. *Traffic Inj. Prev.* 2017, 18, 393–397. [CrossRef]

22. Ferreira, S.; Amorim, M.; Couto, A. Risk factors affecting injury severity determined by the MAIS score. *Traffic Inj. Prev.* 2017, 18, 515–520. [CrossRef]

23. Stevenson, M.; Segui-Gomez, M.; Lescohier, I.; Scala, C.D.; McDonald-Smith, G. An overview of the injury severity score and the new injury severity score. *Inj. Prev.* 2001, 7, 10–13. [CrossRef]

24. International Traffic Safety Data and Analysis Group. Reporting on Serious Road Traffic Casualties. Combining and Using Different Data Sources to Improve Understanding of Non-Fatal Road Traffic Crashes. Available online: www.internationaltransportforum.org (accessed on 30 June 2020).

25. Yao, H.; L, Z.; Lin, Y. Critical boundary of delay spread on urban road traffic network under disruptive traffic accidents. *J. Saf. Syst. Manag.* 2017, 26, 663–669. [CrossRef]

26. Jiang, H.; Yin, T.; Li, X.; Chen, H. Road accident socio-economic loss quantitative estimate methods and indicators. *J. Highw. Transp. Res. Dev.* 2005, 22, 120–124. [CrossRef]

27. Yong, P.; Wang, X.; Peng, S.; Huang, H.; Tian, G.; Jia, H. Investigation on the injuries of drivers and copilots in rear-end crashes between trucks based on real world accident data in china. *Future Gener. Comput. Syst.* 2018, 86, 1251–1258. [CrossRef]

28. Jiang, X.; Zhang, G.P.; Shi, X.; Xia, L. Impact of interacted hazardous actions on injury severity in both-at-fault crashes. *J. Southwest Jiaotong Univ.* 2018, 53, 378–384. [CrossRef]

29. Zhang, L.; Liu, T.; Pan, F.; Guo, T.; Liu, R. Analysis of effects of driver factors on road traffic accident indexes. *China Saf. Sci. J.* 2014, 24, 79–84. [CrossRef]