効果的な交通安全対策立案のための信号交差点安全性
定量評価シミュレーション手法の開発

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1 Introduction

1.1 Background

Signalized intersections are the most critical elements in any transportation network. Their operations considerably affect the performance of the whole road system. Road users of different types in different masses, from different directions and moving at different speeds have to use the same space, resulting in a large number of potential conflicts. Whereas intersections constitute a very small part of the entire transportation network, more than 50% of all motor vehicle accidents occur at intersections. In some European countries, percentages of up to 70% of the total accident number are reported (Kuciembera and Cirillo 1992).

Various operational policies and design layouts have been implemented at signalized intersections all over the world based on the cultural customs, prevailing traffic characteristics and available technologies locally. For instance, signal control has long been the most important operational strategy for traffic on urban streets. Control methods and control systems (hardware and software) differ case by case, as do the objectives. It is no doubt that different operational policies or design layouts possesses benefits as well as drawbacks in terms of reliability and efficiency. However, a reliable tool which can quantitatively evaluate traffic quality and safety is not available yet.

This project aims at developing a microscopic simulation model for the safety evaluation of signalized intersections. This simulation will allow practitioners to evaluate the effects of various improvements in the geometric layouts and operations of signalized intersections on the overall safety performance. For instance, through this microscopic simulation, it would be possible to predict the impacts of adding channelization or adjusting the positions of crosswalks or intersection corner radii. And it can further be applied to modify the signal timings such as all-red intervals. However in order to develop such a simulation model, user behavior must be reasonably reflected.

1.2 Project overview

Figure 1.1 shows the main tasks to be accomplished by this project within the two-years period. This Figure is the same one included in the first project report submitted last year (Report 1, R 1). Several tasks have been completed during the first year such as pedestrian and vehicle data collection by video survey (Tasks 1 & 2) and accident records analyses to identify the most frequent accident types (Task 5). Some tasks could not be completed during the first year such as user behavior analysis and modeling (Tasks 4 & 5). The tasks related to the microscopic simulation model development and the safety evaluation indices (Tasks 8, 9 &10) have been addressed during the second year.
1.3 Safety at signalized intersections

The safety evaluation of signalized intersections is one of the most challenging topics. An accident analysis identified the most prominent type of accidents at urban signalized intersections in Japan. There are mainly five types of conflicts as shown in Figure 2.2. As shown in the first year report angle collisions and left-turning vehicles with pedestrian/cyclist collisions are among the most frequent collisions at signalized intersections. Furthermore, although signalized intersections are operated in a way to give pedestrians a prioritized right of way, more than one-third of the total traffic accident fatalities are pedestrians (Japan National Police Agency, 2010). Thus, in this project, two types of collisions are chosen for the safety evaluation of signalized intersections. Conflicts between left-turning vehicles and pedestrians/cyclists (Figure 1.2d) and angle collisions between clearing right-turning vehicles and starting crossing through traffic (Figure 1.2b), are the subject
conflicts in the modeling and safety evaluation in this project. For the safety evaluation, new indices will be used for each type of conflicts as will be explained in Sections 3.6 and 4.6.

1.4 Outline

This report explains firstly the methodology of the basic models used in the modeling of different conflict types (vehicle path, vehicle speed profile, stop-go decision at the onset of yellow, acceptance of gaps in pedestrian streams). Chapters 3 and 4 expand upon the details of the models used for conflicts of right-turning and left-turning traffic. In Chapter 5 the simulation software developed to apply the models and evaluate the safety of signalized intersections is introduced. The validation of the simulation tool and a case study are explained in Chapter 6. The report closes with conclusions and an outlook to further research (Chapter 7).
2 Methodology of Basic Models

2.1 Overview

All maneuvers analyzed in this project require four basic underlying models to describe the driver behavior (Figure 2.1). Car following and lane changing behavior follows the same principles at intersections and on links. For this, existing models can be used. The models as described here assume free flowing cars. Car following and lane changing behavior is, hence, not further discussed.

Figure 2.1 Basic models underlying turning maneuvers at signalized intersections

The path and speed of vehicles are described in two separate trajectory models. The connection is ensured by the empirical modeling of the input parameters. The trajectory models are explained in Sections 3.3 and 4.4.

The reaction to traffic signals is divided into two aspects: the signal change from red to green (start-up behavior) and the signal change from green to red (stop-go decision). The models have been developed and calibrated for through traffic (start-up, cf. Section 3.5) and right turning traffic (stop-go, cf. Section 2.3.4 and 3.2). Thus, the models focus on specific aspects of these two movements. However, they prove the validity of the approach and represent a basis for generalization.
The reaction of turning vehicles to other travelers is developed for the reaction of left-turning traffic to crossing pedestrians (cf. Section 2.5, 4.3 and 4.5). To realistically model this maneuver the behavior of the pedestrians is analyzed (Section 4.2).

2.2 Path of vehicles

One of the important aspects in analyzing driver behavior, which is a vital element in the safety performance of signalized intersections, is vehicle trajectories. Several existing studies found that there are significant variations in trajectories of turning vehicles dependent on intersection geometry and operational policies. It is rational to assume that such variations might result in creating specific unfavorable conditions which might lead to collisions. In reality, road users behave by anticipating other users’ behavior in order to avoid any collisions with them. Broadly varying road user behavior and trajectories may lead to misunderstanding of other users’ decisions which might result in safety problems. Therefore, it is quite important to consider not only average vehicle maneuvers but also their variation which is affected by the geometric layout of intersections and the interaction with pedestrians.

Modeling individual vehicle trajectories was completed in the first year of the project by applying the Euler-spiral-based approximation methodology. The basic idea is that vehicle trajectories can be represented by modeling the change in the curvature. Thus three types of segments are used; straight lines, circular curves and Euler spiral curves as shown in Figure 2.2. The parameters which represent the three segments are modeled as a function of the geometric characteristics of the intersection, vehicle type and speed. The general forms of the developed empirical models are shown by Equations (2.1) to (2.3).

![Diagram of vehicle trajectory](image)

Figure 2.2 Modeling the trajectory of turning traffic
Where $A_1$ and $A_2$ are entering and exit clothoid parameters ($m$), respectively; $R_{min}$ is the radius of the circular curve ($m$) and $\alpha$, $\beta$, $\gamma$ are model parameters. For detailed information about the assumptions behind this trajectory model, refer to the first year report of the project (R 1).

### 2.3 Speed profile of vehicles

#### 2.3.1 Overview

Section 2.2 described the modeling of the path of turning vehicles. Here the model to represent their speed is introduced. Based on empirical data a mathematical model was chosen that accurately reproduces speed and acceleration behavior of turning vehicles (Subsection 2.3.2). The speed profiles are influenced by the intersection geometry and the approach speeds of the vehicles among others. This influence was empirically modeled as described in Subsection 2.3.3.

#### 2.3.2 Derivation of mathematical model

To accurately model the speed of turning vehicles at signalized intersections, empirically gathered trajectory data has been analyzed. The speed profile of free flowing cars follows a typical shape as shown in Figure 2.3a. From the entering speed $v_{enter}$ the drivers decelerate to the minimum speed $v_{min}$ and accelerate again to the exiting speed $v_{exit}$. The acceleration at the beginning and ending of the maneuver ($a_{enter}/a_{exit}$) is commonly assumed to be zero.

The acceleration does not have to be symmetric to the deceleration. The speed profile can be separated into two parts with the time $t_{min}$ when the minimum speed is reached as the division point.

If this speed profile is described by a function that not only fits well to the speed data itself, but also reflects the acceleration behavior as the derivative of the speed, sufficiently accurate outcomes can be expected. A polynomial of third degree for the speed as a function of the time fulfills this requirement as shown by Equation (2.4).

\[ v = c_1 t^3 + c_2 t^2 + c_3 t + c_4 \]  

(2.4)

The congruency of the shapes of observed and model speed profile is highlighted in Figure 2.3a. The acceleration profile is in this way a polynomial of second degree. Figure 2.3b shows the acceleration for the speed profiles from Figure 2.3a and the model acceleration profile.
Figure 2.3 illustrates that while the jerk as the derivative of the acceleration varies markedly due to its sensitivity to speed changes and the limited precision of the data acquisition, the general trend is still represented by the chosen function for the speed.

The principle shape of the speed function and its first and second derivative are illustrated in Figure 2.3d. This general speed profile for turning traffic not influenced by signals, other vehicles, or pedestrians is called ideal speed profile. It is divided into the inflow of the curve and the outflow of the curve, with the minimum speed as the division between the two regions. This general shape can be used for both left-turning and right-turning vehicles.

2.3.3 Empirical modeling

Most of the coefficients of the speed function are determined by constraints (speed \( v \) and acceleration \( a \) at the beginning and the ending of the maneuver). The remaining coefficients and unknowns reflect the difference in driver behavior due to individual characteristics and due to
intersection properties. These unknowns are modeled as random variables with intersection properties as influencing factors. Figure 2.4 highlights the constraints of the two parts of the ideal speed profile (inflow and outflow), and the eight coefficients used in the speed function (four for each part).

![Figure 2.4 Constraints of the ideal speed profile](image)

The characteristic parameters for the individually chosen random distributions ($X$) are modeled as a linear combination of the influencing factors ($X_i$) as shown in Equation (2.5). The overall process is illustrated in Figure 2.5.

$$x = \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_n X_n$$ (2.5)

Trajectory data from signalized intersections (cf. R 1) has been used to calibrate the speed profiles. The raw data first had to be processed. The data was separated into the inflow and outflow part with the minimum speed marking the boundary. Least square fitting was used to derive the coefficients and unknowns of the speed function which has been described in Subsection 2.3.2. Outliers have been determined by individual visual inspection of the profiles as illustrated in Figure 2.6 (black and dark red respectively represent the observed speed and acceleration; the light colors show the best fit for inflow and outflow).

The thus derived coefficients can be used to statistically analyze the influence of different factors on the shape of the speed profile. Three of the four coefficients $c_1$ to $c_4$ are dependent on constraints (speed and acceleration at the beginning and ending of the profile parts). The remaining coefficient and characteristic points of the speed profile (position along the vehicle path, minimum speed) incorporate the influences by intersection geometry and driver characteristics. The following factors have been analyzed for correlation with the speed function characteristics:
• approach speed $v_{enter}$
• exiting speed $v_{exit}$
• intersection angle
• curb radius $R_c$
• distance of the hard nose to the trajectory tangent intersection $\Delta HN$
• lateral distance of the vehicle in the exit from the curb

The speed profiles used in the simulation are, thus, dependent on the empirically modeled parameters and constraints as highlighted in Figure 2.7.

Due to sample limitations, the results of the empirically modeling can only be seen as preliminary. However, it already reflects well the impact of different intersection layouts, speed levels, etc. as will be demonstrated in a case study (Chapter 6). The details of the empirical models are derived separately for the right-turning (Section 3.4) and left-turning (Section 4.5) vehicles.

Figure 2.5 Illustration of overall speed profile modeling process

Figure 2.6 Visual comparison of fitted and observed speed and acceleration profiles (Outlier)
2.3.4 Connection between path and speed profile

The speed profile is related to the intersection indirectly by relating it to the path of the vehicle. The distance between the beginning of the turning path of the vehicle as described in Section 2.2 and the position where the vehicle reaches its minimum speed is empirically modeled as a random distribution. In this way the path, the speed profile and the intersection geometry are connected to each other (Figure 2.8).

2.4 Stop-go decision at the onset of yellow

When drivers approach an intersection and they observed the signal change from green to yellow, they need to make a decision either to stop or to go through the intersection. Drivers’ stop-go decision is a function of several parameters such as time to stop line at the onset of yellow, all-red interval, vehicle speed and vehicle type. In this study, the probability that a vehicle will stop is modeled using a Logit model as shown in Equation (2.6).

\[
P_{\text{stop}} = \frac{\exp(V_{\text{stop}})}{1 + \exp(V_{\text{stop}})}
\]  

(2.6)

Where \(P_{\text{stop}}\) is the probability to stop at the onset of yellow and \(V_{\text{stop}}\) is stopping utility function. For detailed information about model assumptions and estimation refer to the first year report of the project.
2.5 Drivers acceptance to gaps between pedestrians

Gap is the time difference between two subjects arriving at the same position. In the vehicle-pedestrian conflicts, the available gaps between pedestrians for drivers are defined as the time difference between two pedestrians arriving at the conflict point. These gaps are opportunities for drivers to cross. If no suitable gap is available when the vehicle will reach the crosswalk, the driver has to adjust the speed, if necessary to a full stop. The driver will then have to wait until an acceptable gap appears or until all pedestrians have cleared the crosswalk. Therefore, whether available gaps will be accepted or rejected is significantly affected by driver behavior. The occurrence of gaps depends on the characteristics of pedestrian movements.

For the purpose of this research, a gap is defined as the time difference between two successive pedestrians passing the conflict point while a lag is defined as the time needed for one pedestrian to reach the conflict point. Pedestrian movements can have their origin at either the near side or the far side of the crosswalk with reference to conflicting vehicles. Near-side pedestrians are those who start crossing from the side of the vehicular traffic that is exiting the intersection while far-side pedestrians are those who start crossing from the side of the incoming vehicular traffic as shown in Figure 2.9. Considering the vehicle size, the gap is the time difference between the first pedestrian crossing the far edge of the vehicle trajectory and the second pedestrian crossing the near edge of
the vehicle trajectory. The lag is the time between the pedestrian crossing the near edge of the vehicle trajectory and the vehicle arriving at the conflict point as shown in Figure 2.9.

Gaps and lags are calculated when the turning vehicle arrives at the near border of the crosswalk. The gaps between pedestrians who crossed the conflict point before the vehicle reaches the crosswalk are defined as the “unavailable gaps” and they are not considered in this research. The gaps/lags which are used by drivers are called “accepted gaps/lags”, while other gaps/lags which are available but not utilized by drivers are called “rejected gaps/lags”.

Figure 2.9 Pedestrian origin-destination and gap/lag definition considering vehicle size
Generally, lags/gaps are classified into five different types depending on the pedestrians’ direction of movement as shown in Figure 2.10.

Type A: lags of pedestrians approaching from the near side of the crosswalk;
Type B: lags of pedestrians approaching from the far side of the crosswalk.
Type C: gaps between two pedestrians approaching from the near side of the crosswalk;
Type D: gaps between two pedestrians approaching from the far side of the crosswalk;
Type E: gaps between a pedestrian approaching from the near side of the crosswalk and another one approaching from the far side of the crosswalk.

In order to estimate the gap/lag acceptance probability distribution for each type of the defined gaps/lags, empirical data is necessary. After collecting the required data, gaps/lags are categorized into several classes. The gap/lag acceptance probability for class $i$ is calculated according to equation (2.7).

$$P(x) = \frac{\text{No. Accepted gaps/lags}}{\text{Total No. of observed gaps/lags}} \quad \text{(in category i)}$$

A Cumulative Weibull Distribution is used to fit the observed gap/lag acceptance probability distributions. The Weibull Distribution is a widely used function to represent the breakdown probability on highways and expressways. It is also widely used to represent various gap acceptance conditions between different travelers in the transportation network. Equation (2.8)
presents the Cumulative Weibull Distribution function with two parameters; the shape parameter $\alpha$ and the scale parameter $\beta$.

\[
P(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^\alpha}
\]  

(2.8)

Where $P(x)$ is the acceptance probability of gap/lag $x$, $\alpha$ and $\beta$ are Weibull Distribution parameters.
3 Angle Collisions between Right-turning and Cross Traffic

3.1 Overview

To represent angle collisions, the behavior of clearing right-turning vehicles and conflicting through traffic need to be well represented inside the simulation environment. The required models to represent angle collisions are summarized in Figure 3.1b). They are divided into models representing the behavior of the clearing right-turning vehicles (stop-go decision and trajectory) and models representing the behavior of the entering through traffic in the cross street (start-up behavior). All of these models have already been developed during the first year of the project, except the speed profile model as part of the trajectory modeling which will be presented in detail here.

Figure 3.1 Required models to represent the conflict between clearing right-turning vehicles and entering through vehicles

3.2 Stop-go behavior at the onset of yellow

As explained in Section 2.3, the probability of drivers to decide to stop when approaching the intersection at the onset of the yellow signal is modeled by using a Logit Model (Equation (2.6)). The stopping utility function is assumed to have a linear form with independent variables as shown in Table 3.1. By using Equation (2.6) and Table 3.1, the stopping probability can be estimated and then the stop-go decision can be assigned randomly. For detailed information about the assumptions behind this stop-go decision model, refer to the first year report of the project.
Table 3.1 Right-turning vehicle stop-go model parameter estimation

<table>
<thead>
<tr>
<th>Explanatory variable</th>
<th>Parameter of entering Euler spiral curve $A_1$ (m) Parameters (t-values)</th>
<th>Parameter of exit Euler spiral curve $A_2$ (m) Parameters (t-values)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Const.</td>
<td>Minimum speed $V_{min}$ (km/h)</td>
</tr>
<tr>
<td></td>
<td>-8.65 (-3.33)</td>
<td>0.294 (4.48)</td>
</tr>
<tr>
<td></td>
<td>Distance from IP point to hard nose (m)*</td>
<td>$D_{HN,IN}$ 0.172 (6.90)</td>
</tr>
<tr>
<td></td>
<td>Modified R²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sample Size</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Refer to Figure 2.2.

**3.3 Path of right-turning vehicles**

As explained in Section 2.1, the path of turning traffic is modeled by a combination of straight, circular and Euler spiral curves. The estimated models for the curve segments which are shown in Equations (2.1), (2.2) and (2.3) are listed in Table 3.2 and Table 3.3. It was assumed that the entering spiral curve parameter $A_1$ and the exit spiral curve parameter $A_2$ are dependent on the minimum speed along the turning maneuver. This minimum speed is modeled for both parts of the trajectory estimation: path and speed.

Thus $V_{min}$ is modeled assuming Normal Distribution. For detailed information refer to the first year report of the project.
Table 3.3 Results of estimated minimum radius and minimum speed for right-turning vehicles

<table>
<thead>
<tr>
<th>time</th>
<th>Explanatory variables</th>
<th>Radii of circular curve $R_{min}$ (m) Parameters (t-values)</th>
<th>Minimum speed $V_{min}$ (km/h) Parameters (t-values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>Const.</td>
<td>-</td>
<td>4.49 (2.62)</td>
</tr>
<tr>
<td></td>
<td>Intersection angle (deg)</td>
<td>0.0621 (3.80)</td>
<td>0.0717 (5.57)</td>
</tr>
<tr>
<td></td>
<td>Distance from IP point to hard nose (m) * $D_{HN, IN}$</td>
<td>-</td>
<td>0.00920 (4.52)</td>
</tr>
<tr>
<td></td>
<td>Minimum between $D_{HN, IN}$ and $D_{HN, OUT}$</td>
<td>0.159 (4.35)</td>
<td>-</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>Minimum speed $V_{min}(km/h)$</td>
<td>0.438 (7.63)</td>
<td>0.380 (13.13)</td>
</tr>
<tr>
<td></td>
<td>Const.</td>
<td>-</td>
<td>0.124 (2.69)</td>
</tr>
<tr>
<td></td>
<td>Intersection angle (deg)</td>
<td>-</td>
<td>1.71 (4.57)</td>
</tr>
<tr>
<td></td>
<td>Minimum speed $V_{min}(km/h)$</td>
<td>0.130 (17.4)</td>
<td>-</td>
</tr>
<tr>
<td>Sample Size</td>
<td>151</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Refer to Figure 2.2.

3.4 Speed profile of right-turning vehicles

The basic principles of the speed of vehicles when turning at a signalized intersection have been explained in Section 2.3. The particularities of right-turning speed profiles are incorporated into the model by empirical analysis of the speed function coefficients and constraints. Table 3.4 shows the constraints for the speed equation (2.4) with the acceleration as the first derivative and their four unknowns for both the inflow and outflow part of the ideal speed profile (cf. Figure 2.4). This system of linear equations is underdetermined. The coefficient $c_1$ (inflow and outflow) and the minimum speed $v_{min}$ are empirically modeled.

Table 3.4 Constraints and modeled parameters for ideal speed profile

<table>
<thead>
<tr>
<th>Parameters</th>
<th>inflow</th>
<th>outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v$ (in)</td>
<td>$v_{enter}$</td>
<td>$v_{min}$</td>
</tr>
<tr>
<td>$v$ (out)</td>
<td>$(v_{min})$</td>
<td>$v_{exit}$</td>
</tr>
<tr>
<td>$a$ (in)</td>
<td>$a_{enter}$</td>
<td>0</td>
</tr>
<tr>
<td>$a$ (out)</td>
<td>0</td>
<td>$a_{exit}$</td>
</tr>
<tr>
<td>$t$ (out)</td>
<td>$(t_{exit} - t_{min})$</td>
<td></td>
</tr>
<tr>
<td>Degree of freedom/constraints</td>
<td>5/3</td>
<td>5/4</td>
</tr>
<tr>
<td>Modeled parameter</td>
<td>$v_{min}$, $c_{I,in}$</td>
<td>$c_{I,out}$</td>
</tr>
</tbody>
</table>

In addition to $v_{min}$, $c_{I,in}$ and $c_{I,out}$ the position of the speed profile with reference to the path of the vehicle $x_{min}$ is empirically modeled (cf. Subsection 2.3.4). The observed behavior of vehicles reveals that these parameters are related to certain intersection characteristics, namely the
intersection angle and the position of the hard nose (cf. Figure 2.2). Correlation charts with the different influencing factors are shown on the following pages. The linear trend is shown with the mean plus/minus the standard deviation indicated by dashed lines. The parameters are modeled as randomly distributed values. For the coefficients characterizing the random distribution, a linear combination of the most important influencing factors has been used. The coefficients are given in a table for each speed profile parameter.

**Coefficients $c_{1,in}$ (inflow) and $c_{1,out}$ (outflow)**

The coefficient $c_1$ is a jounce parameter (first derivative of the acceleration). It determines the shape of the speed profile. For the inflow it is positive, for the outflow it is negative. The distribution shows a distinct positive skew. Therefore, a Gamma Distribution was chosen to represent the data as shown in Figure 3.2.
While for the outflow no significant influencing factors on the shape and scale of the Gamma Distribution could be determined, a correlation between the coefficient of the inflow and intersection angle and entering speed can be discerned (Table 3.5).

### Table 3.5 Models of $c_{1,in}$ and $c_{1,out}$ coefficients for right-turning vehicles

<table>
<thead>
<tr>
<th>Gamma Distribution</th>
<th>Parameters</th>
<th>$c_{1,in}$ $X\sim \Gamma(\alpha, \beta)$</th>
<th>$c_{1,out}$ $X\sim \Gamma(\alpha, \beta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Estimate (Sig.)</td>
<td>Estimate (Sig.)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Const</td>
<td>9.412827 (0.000)</td>
<td>2.089874 (0.000)</td>
</tr>
<tr>
<td></td>
<td>Intersection angle (degrees)</td>
<td>-0.0759988 (0.000)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Entering speed (m/sec)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Const</td>
<td>-0.0548171 (0.000)</td>
<td>0.0231397 (0.000)</td>
</tr>
<tr>
<td></td>
<td>Intersection angle (degrees)</td>
<td>0.0007814 (0.000)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Entering speed (m/sec)</td>
<td>0.0015876 (0.006)</td>
<td>-</td>
</tr>
</tbody>
</table>

### Minimum speed

The distribution of minimum speeds of right-turning vehicles is symmetric as shown in Figure 3.3 thus a Normal Distribution is used to fit the minimum speed distribution. However, this distribution is affected by different parameters, for instance intersection angle, entering speeds and vehicle type. Since sufficient data to analyze the effect of heavy vehicles is not available, the analysis is limited to approaching speed and intersection angle. Figure 3.4 indicates a linear correlation between the minimum speed and the entering speed and the intersection angle. The two dashed lines stand for the area around the mean with The final model for minimum speed is presented in Table 3.6.

![Figure 3.3 The distribution of observed minimum speeds $v_{min}$ for right-turning vehicles](image)
The position of the minimum speed \( v_{\min} \) on the vehicle path is defined as the distance from the beginning of the turning path of the vehicle (first clothoid) of the vehicle path in the intersection to the point where the minimum speed \( v_{\min} \) occurs (cf. Subsection 2.3.4). As shown in Figure 3.5 \( x_{\min} \) follows a symmetric distribution; therefore, it is modeled as a Normal Distribution. The final model for \( x_{\min} \) is presented in Table 3.6.
a) Intersection angle and $x_{\text{min}}$

b) Entering speed $v_{\text{enter}}$ and $x_{\text{min}}$

c) Distance from IP point to hard nose $D_{\text{HN,OUT}}$ and $x_{\text{min}}$

Figure 3.5 The distribution of observed $x_{\text{min}}$ (position of minimum speed) for right-turners

Figure 3.6 Correlation between several parameters and position of minimum speed $x_{\text{min}}$ for right-turning vehicles
3.5 Start-up behavior of through traffic

At intersections with the common lag-lag phasing plan (単純4現示制御), it was observed that the clearing behavior of right-turning traffic affects the start-up behavior of the following cross through traffic. Thus, the start-up response time (SRT) of the through traffic is modeled assuming a Weibull Distribution. As shown in Equation (3.1), the Weibull Distribution has three distribution parameters, shape \( \alpha \), scale \( \beta \), and location \( \gamma \). Each of them was estimated by influencing factors such as intersection geometry, signal control, and traffic conditions. More specifically, explanatory variables include the distance between the opposite stop-lines, set-back of the stop-line, the entering distance \( x_{\text{Se}} \), late exit time \( x_{\text{LET}} \), length of the all-red time \( x_{\text{AR}} \), signal phasing plan (dummy variable: the permitted-and-protected right-turn phasing plan or the dual-lagging protected-only right-turn phasing plan), and vehicle type (dummy variable, \( x_{\text{heavy}} \): passenger car or heavy vehicle). Based on statistical tests, the basic structure of the final models is described through Equations (3.1)–(3.4), and the estimated coefficients are presented in Table 3.7.

\[
\alpha = a_0 + a_{\text{heavy}}x_{\text{heavy}}
\]

\[
\beta = b_0 + b_{\text{Se}}x_{\text{Se}} + b_{\text{AR}}x_{\text{AR}} + b_{\text{protected-only}}x_{\text{protected-only}}
\]

\[
\gamma = c_0 + c_{\text{LET}}x_{\text{LET}}
\]

Where, \( a_0, b_0, \) and \( c_0 \) are constants; \( a_{\text{heavy}}, b_{\text{AR}}, b_{\text{protected-only}}, \) and \( c_{\text{LET}} \) are coefficients. The empirically estimated constants and coefficients are listed in Table 3.7. For detailed information about the estimated start-up response time SRT model refer to the first year report of the project.

After determining the SRT, it is necessary to estimate the acceleration of the entering through vehicle until it reaches the conflict point. An empirical analysis was conducted to understand the distribution of this acceleration. Finally, as it was reported in the first year report, the entering acceleration is modeled assuming a Normal Distribution. The mean and standard deviation are modeled as a function of explanatory variables as shown in Table 3.8. The SRTs were divided into two populations by taking 0.7s as the threshold value. Both populations are described by Normal Distributions as shown in Table 3.8. The results suggest that hurry-start vehicles adjust their acceleration rates based on the onset time of green, while the other vehicles adjust their acceleration rates according to late exit time LET of the clearing vehicles. For detailed information refer to the first year report of the project.
After modeling the clearing behavior of right-turning traffic and the starting behavior of crossing through traffic, the conflict between these two traffic movements can be evaluated and assessed. Various safety indices can be used to quantify these conflicts such as post encroachment time (PET) or time to collision (TTC). In this study, a unique index is proposed for the safety assessment of angle collision between right-turning and cross traffic. The proposed index is called Angle Collisions Index ACI. This index is based on combining two dimensions, the frequency and the potential severity of vehicle-vehicle conflicts.

In past research, the frequency or rate of reported accidents is commonly used for the evaluation of the safety at intersections. When applying such methods, comprehensive historical accident data is necessary comprising at least several years. Therefore, this accident analysis is suitable for long

### Table 3.7 Estimated coefficients of the SRT model

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficients</th>
<th>t values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dummy variable of vehicle type, $a_{\text{heavy}}$ (1: heavy vehicle; 0: otherwise)</td>
<td>-3.40</td>
<td>-2.95</td>
</tr>
<tr>
<td>Constant $a_0$</td>
<td>11.8</td>
<td>7.33</td>
</tr>
<tr>
<td>Entering distance $b_{\text{SE}}$ [m]</td>
<td>-0.0106</td>
<td>-5.49</td>
</tr>
<tr>
<td>$\beta$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dummy variable of signal phasing plan, $b_{\text{protected-only}}$ (1: the dual-lagging protected-only g right-turn phasing plan; 0: otherwise)</td>
<td>0.274</td>
<td>3.30</td>
</tr>
<tr>
<td>Constant $b_0$</td>
<td>13.9</td>
<td>7.65</td>
</tr>
<tr>
<td>Late exit time, $x_{\text{exit}}$ [s]</td>
<td>-0.0597</td>
<td>-5.47</td>
</tr>
<tr>
<td>Constant $c_0$</td>
<td>11.8</td>
<td>6.56</td>
</tr>
<tr>
<td>$\rho^2$</td>
<td></td>
<td>0.56</td>
</tr>
<tr>
<td>Sample size</td>
<td>1189</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3.8 Estimated parameters of the acceleration model for the entering though vehicles

<table>
<thead>
<tr>
<th>Parameters of Normal Distribution</th>
<th>Coefficients</th>
<th>t values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SRT &lt; 0.7s$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$ Start-up response time, SRT [s]</td>
<td>0.246</td>
<td>13.8</td>
</tr>
<tr>
<td>Constant</td>
<td>1.63</td>
<td>55.3</td>
</tr>
<tr>
<td>$\sigma$ Start-up response time, SRT [s]</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>Constant</td>
<td>0.374</td>
<td>20.5</td>
</tr>
<tr>
<td>Sample size</td>
<td>217</td>
<td></td>
</tr>
<tr>
<td>$SRT \geq 0.7s$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$ Late exit time, LET [s]</td>
<td>-0.0369</td>
<td>-5.79</td>
</tr>
<tr>
<td>Constant</td>
<td>1.92</td>
<td>106.0</td>
</tr>
<tr>
<td>$\sigma$ Late exit time, LET [s]</td>
<td>-0.0123</td>
<td>-2.27</td>
</tr>
<tr>
<td>Constant</td>
<td>0.436</td>
<td>34.7</td>
</tr>
<tr>
<td>Sample size</td>
<td>879</td>
<td></td>
</tr>
</tbody>
</table>

### 3.6 Safety Indices

After modeling the clearing behavior of right-turning traffic and the starting behavior of crossing through traffic, the conflict between these two traffic movements can be evaluated and assessed. Various safety indices can be used to quantify these conflicts such as post encroachment time (PET) or time to collision (TTC). In this study, a unique index is proposed for the safety assessment of angle collision between right-turning and cross traffic. The proposed index is called Angle Collisions Index ACI. This index is based on combining two dimensions, the frequency and the potential severity of vehicle-vehicle conflicts.

In past research, the frequency or rate of reported accidents is commonly used for the evaluation of the safety at intersections. When applying such methods, comprehensive historical accident data is necessary comprising at least several years. Therefore, this accident analysis is suitable for long
term a posteriori assessments. Different alternative intersection layouts or signal timing plans cannot be assessed a priori.

In those cases, the traffic conflict technique (TCT) is applicable in which time indices, e.g. post encroachment time (PET), suggested by Allen, et al. (1978) are usually the measures for safety or risk. However, most of them are initially proposed for estimating safety when gap-acceptance or merging maneuver occur during the green intervals. Very few of them have been widely accepted as a safety measure for signal change intervals (intergreen intervals), due to the complicated traffic flow during this interval. For instance, Tang and Nakamura (2008) proposed the PET as a measure for safety performance during intergreen intervals. A PET correspondent to a change of phases is then defined as the elapsed time from when the last clearing vehicle in the previous phase passes the conflict point till when the first entering vehicle released in the subsequent phase arrives there. In this study, PET is used to estimate the number of conflicts. Conflicts are defined as encroachments between two vehicles with a PET of less than \( t_{sec} \).

However, the PET alone cannot assess the safety of angle collisions, for example the impulse of the vehicles involved in the conflict is not considered, although it is a very important factor in determining the severity of a potential accident. Therefore the proposed Angle Collision Index is defined as in Equation (3.5) to incorporate both the frequency and the potential severity of conflicts.

\[
AGI = \frac{\Delta k_e}{e^{\text{PET}}}
\]  
(3.5)

\( \Delta k_e \) is the change in the total kinetic energy before and after the collision. The term \( e^{\text{PET}} \) is used to weight the conflicts depending on the value of PET. As the PET becomes shorter, the likeliness of the conflict becomes higher.

To estimate the change in kinetic energy \( \Delta k_e \), the following assumptions are made:

- The vehicles undergo a perfectly inelastic collision.
- The two vehicles move with the same speed together after the collision.
- The friction between the vehicles and the road can be neglected.
- The loss in Energy reflects how much energy is released if the collision occurs.
- The system is isolated, where the momentum will be conserved.

Figure 3.7 illustrates the assumed kinetic energy concept after a collision. Since the collision environment is assumed as being isolated, the momentum is conserved along both reference axes as shown in Figure 3.7c). Thus Equations (3.6) and (3.7) can be derived. By solving these equations, the change in kinetic energy \( \Delta k_e \) can be estimated as shown in Equation (3.8).
This index will be used as the output of the simulation model for the safety assessment of angle collisions at signalized intersections.

To demonstrate the sensitivity of PCI to PET and conflicting vehicles speed, Figure 3.8 is presented. It assumes a conflict angle of 90 degrees between the two conflicting movement, and a weight of 1500kg for each vehicle with equal speeds. It is rational to see that as PET increases the value of ACI decreases. If PET becomes higher than 5 seconds, the value of ACI becomes negligible. Furthermore at a constant PET, when the speeds of the conflicting vehicles increase,
ACI increases as shown in Figure 3.8. This is quite rational since it reflects that the severity of a conflict increases as the speed of any of the conflicting vehicles increases.

Figure 3.8 The sensitivity of ACI to PET and the speed of conflicting vehicles
4 Left-turning Vehicle Conflicts with Pedestrians

4.1 Overview

Left-turning vehicles are modeled based on four separate models as shown in Figure 4.1. Firstly the behavior of the pedestrians on the crosswalk is analyzed (Section 4.2). Secondly the path of the turning vehicles is modeled (Section 4.4). The vehicles can only pass the crosswalk when sufficient gaps in the pedestrian stream are available. The assessment of the gaps is described in the gap acceptance model (Section 4.3). In addition to the intersection geometry and the driver characteristics, the gap acceptance influences the speed of the vehicles. The speed profile of the turning vehicles is analyzed in Section 4.5. The basic principles of the mentioned models have been described in Chapter 2. Based on these models, conflicts of left-turning vehicles with pedestrians can be assessed by using reasonable safety indices which is discussed in Section 4.6.

4.2 Pedestrian behavior analysis

4.2.1 Methodology

Many factors such as visibility, geometric layout of the intersection, driver behavior while turning and pedestrian behavior influence conflicts between pedestrians and left-turning vehicles. Most of the existing studies which try to analyze the mechanism of such collisions concentrate on driver behavior assuming that it is the most critical factor in determining pedestrian-vehicle collisions. Road users try to anticipate other users’ behavior in order to avoid any collisions with them. Widely varying road user behavior and trajectories may lead to misunderstanding of other users’ decisions which might result in safety problems. Therefore, it is quite important to consider not only vehicles’ maneuver but also pedestrians’ maneuver and its variation which are affected by the

![Diagram](image)

Figure 4.1 Required models to represent the conflict between left-turners and pedestrians
geometric layout of intersections, signal timing, and the existence of turning vehicles.

A preliminary macroscopic analysis on pedestrian speed considering the existence of turning vehicles was not successful in finding any significant relationship. Therefore, a microscopic approach is necessary to tackle pedestrian reaction to turning vehicles. Due to the limited time and the complexity of pedestrian maneuver, this study focuses on the effect of pedestrian signal timing and crosswalk geometry upon pedestrian speed at crosswalks as a first step.

In this study, two different spot speeds and two different travel speeds are defined and estimated for each observed pedestrian. Figure 4.2 illustrates the estimated speeds which are defined as follows:

- **Entering speed** \( (v_{in}) \): The spot speed at the entering edge of the crosswalk \( (m/sec) \).
- **Exit speed** \( (v_{out}) \): The spot speed at the exit edge of the crosswalk \( (m/sec) \).
- **First half travel speed** \( (v_1) \): The travel speed in the first half of the crosswalk \( (m/sec) \).
- **Second half travel speed** \( (v_2) \): The travel speed in the second half of the crosswalk \( (m/sec) \).

Figure 4.2 shows how to estimate travel speeds \( (v_1 \text{ and } v_2) \). Pedestrian origin-destination is defined as pedestrian movement direction which is divided into two categories; near-side or far-side. One of the reasons behind dividing pedestrians into far-side and near-side is to macroscopically analyze the effect of turning vehicles on pedestrian speed. When comparing \( v_1 \) and \( v_2 \), it is important to remember that the first half of the crosswalk for near-side pedestrians is the second half for far-side pedestrians. In the analysis, pedestrians are also classified into two categories; pedestrians who face

---

**Figure 4.2** Definition of pedestrian spot speeds and travel speeds
Pedestrian signal timing is divided into six intervals; \( R_1 \), \( G_1 \), \( G_2 \), \( G_3 \), \( PFG \) and \( R_2 \) as shown in Figure 4.3. \( G_1 \) is defined as 5 s long, assuming that this time in average is enough for the waiting pedestrians to discharge at the edge of the crosswalk. The second interval \( G_2 \) is defined based on the time needed for one pedestrian to cross a half of the crosswalk by assuming a speed of 1 m/sec.

In this way \( G_2 \) is independent of a pedestrian platoon crossing at the same time. The remaining pedestrian green time is defined as \( G_3 \). Pedestrians who start crossing before the beginning of pedestrian green \( PG \) are classified as crossing during \( R_1 \) while those who start crossing after the end of pedestrian flash green \( PFG \) are classified as crossing during \( R_2 \). \( R_1 \) is defined as being 10 s, the remaining pedestrian red time is \( R_2 \).

\( v_1 \), \( v_2 \) and \( v_{out} \) for each pedestrian are categorized depending on the entering time to the crosswalk. For example, if a pedestrian entered the crosswalk in \( G_1 \), then \( v_1 \), \( v_2 \) and \( v_{out} \) for that pedestrian will be classified as crossing during \( G_1 \).

### 4.2.2 Data collection and processing

In order to analyze the pedestrian speed at crosswalks, video data was collected at three signalized crosswalks. Table 4.1 presents the observation dates, the geometric and signal timing characteristics of the study sites. All these sites are located in Nagoya City, Japan. The observed crosswalks have significantly different geometric and operational characteristics such as crosswalk.

---

**Table 4.1 Surveyed site characteristics**

<table>
<thead>
<tr>
<th>Intersection name</th>
<th>Crosswalk position</th>
<th>Dimensions ( w \text{m}\times L \text{m} )</th>
<th>Survey hours</th>
<th>Cycle Length (sec)</th>
<th>Pedestrian green time ( PG ) (sec)</th>
<th>Pedestrian flashing green time ( PFG ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaike</td>
<td>East Leg</td>
<td>9m\times20m</td>
<td>13:00-15:00</td>
<td>140</td>
<td>35</td>
<td>5</td>
</tr>
<tr>
<td>Suemori-Dori2</td>
<td>South Leg</td>
<td>7m\times18m</td>
<td>09:00-12:30</td>
<td>140</td>
<td>47</td>
<td>5</td>
</tr>
<tr>
<td>Nishi-Osu</td>
<td>North Leg</td>
<td>5m\times36m</td>
<td>09:00-12:30</td>
<td>160</td>
<td>38</td>
<td>5</td>
</tr>
</tbody>
</table>
length and signal timing parameters. All the observed intersections are operated by a 4-phase plan where a shared through-left turning phase is followed by an exclusive right turning phase as shown in Figure 4.2. The trajectories of pedestrians are extracted from video data by using the image processing system TrafficAnalyzer (Suzuki and Nakamura, 2006). The position of each pedestrian was extracted every 0.5 seconds. The video coordinates were converted to global coordinates. The point where the feet of the pedestrian are touching the ground is the reference observation point. All video observations were done from high buildings around the intersections, thus for all video tapes, the observation angle is large which enables tracking pedestrians without facing any obstacles.

It is important to note that all observed sites have high through traffic demand, thus most of the right turning vehicles turn in their exclusive phase which explains why most of the pedestrian involved in conflicts are with left turning vehicles. Table 4.2 presents the observed number of pedestrians who start crossing in various signal intervals, who face (“with”) or do not face (“without”) turning vehicles, and average left turning vehicle demand (L.T.V). According to observations, the number of pedestrians who start crossing after the end of pedestrian flash green is
very small while those who start crossing before pedestrian green starts is higher, especially at Imaike Intersection where pedestrian demand is much higher than at other sites.

### 4.2.3 Analysis of pedestrian speeds

There are several factors that might affect the variations in pedestrian speeds. According to the conducted analysis, signal timing, crosswalk length and the existence of turning vehicles are the most significant factors that affect pedestrian speeds while crossing.

Figure 4.4 shows the mean and the 85 percentile of pedestrians’ entering speeds $v_{in}$ from the near-side and far-side of the crosswalk. It is clear that the average entering speed increases as the time of pedestrian green proceeds. This tendency is understandable, since pedestrians who see the green indication early before reaching the crosswalk tend to hurry up so they can cross before the signal change. This phenomenon is affected by crosswalk length. It is found that both near-side and far-side average pedestrian entering speeds during G3 at Nishiosu intersection are significantly higher (at 95% confidence level) than other sites. Due to the extremely long crosswalk at Nishiosu intersection, pedestrians hurry up when they approach the crosswalk during pedestrian green interval trying to secure as much time as possible for the long crossing distance. This also explains why the differences between the entering speeds in G1, G2 and G3 increase as crosswalk length...

---

**Figure 4.4** The mean and 85 percentile of entering speeds $v_{in}$ in different signal intervals.
increases. Simultaneously, it is clear that the average entering speeds of near-side pedestrians are higher than far-side pedestrians especially during G3.

Figure 4.5 shows that the mean exit speed $v_{out}$ of far-side pedestrians is significantly higher than that of near-side pedestrians which can be attributed to the effect of exiting turning vehicles. There is no clear difference in exiting speeds between G1 and G2. However, exiting speeds are significantly higher in G3 compared to G1 and G2, which means that pedestrians in the second half of signal green interval tend to exit the crosswalk faster compared to the first half of the green interval.

It is interesting to see that the exit speed $v_{out}$ distribution during PFG of far-side pedestrians is significantly higher compared to that of near-side pedestrians as shown in Figure 4.5. This can be referred to the effect of turning vehicles since far-side pedestrians exit from the side where they might encounter conflicts with turning traffic. This explains why far-side pedestrians hurry up when they reach the second half of the crosswalk which is simply to clear the conflict area as fast as possible. Meanwhile, near side pedestrians exit from the side where they don’t have conflicts with turning traffic, thus they feel safer which make them slow down. Such behavior is very critical since drivers might not be able to predict such change in pedestrian speeds which might lead to misjudgments and wrong decisions.

Figure 4.6 and Figure 4.7 show the mean and the 85 percentile of first half $v_1$ and second half $v_2$ travel speeds and for near-side and far-side pedestrians respectively. For near-side pedestrians,
there were no significant differences (95% significance level) between $v_1$ distributions in G1 and G2. This also applies to $v_2$ distributions. However at Suemori-Dori2 intersection, the means of $v_1$ and $v_2$ for near-side pedestrians in G1 and G2 are significantly different as shown in Figure 4.6. The inconsistent results at Suemori-Dori2 intersection might be due to the insufficient sample size. The travel speed distributions in G3 are significantly different from those in G1 and G2 at all intersections. This can be explained that pedestrians predict how long time is available before the termination of pedestrian green interval, which makes them speed up.

Generally, it is concluded that the travel speeds of the pedestrians waiting at the beginning of green interval (G1) from near-side and far-side are quite similar. The significant change occurs in the second half of pedestrian green interval (G3). This phenomenon is very important to be considered since most of the severe conflicts between pedestrians and turning vehicles occur during the second half of pedestrian green in which number of crossing pedestrians becomes smaller. Moreover, by comparing the travel speeds ($v_1$ and $v_2$) at Nishiosu Intersection with those at Imaike and Suemori-Dori2 intersections, it is clear that travel speeds at Nishiosu intersection are significantly higher (95% significance level) as shown in Figure 4.6 and Figure 4.7, which can be referred to the extremely long crosswalk.

In Figure 4.4, Figure 4.5, Figure 4.6, and Figure 4.7, the entering, exit and travel speeds during pedestrian flash green interval PFG are presented. The speeds during PFG are presented for pedestrians at Imaike Intersection only, since the observed number of pedestrian during PFG at the
other sites is very small. The distributions of entering speeds for far-side and near-side pedestrians in PFG are not significantly different as shown in Figure 4.4. This somehow contradicts with the results during G3 where near-side pedestrians have significantly higher entering speeds compared to far-side pedestrians at all sites. Furthermore, it is concluded that the average of entering speeds during PFG is significantly higher than that of G1, G2 and G3.

Regarding the effect of turning vehicles, the mean travel speed ($v_1$ and $v_2$) for far-side pedestrians who faced (with) and did not face (without) turning vehicles are significantly different at 95% confidence level while no significant differences can be found for near-side pedestrians. Basically, the effect of turning vehicles on pedestrian speed is totally dependent on the circumstances when they meet, such as vehicle speed, vehicle type, pedestrian signal timing, etc. Therefore, it is difficult to reasonably assess the effects of turning vehicles in macroscopic analysis level.

### 4.2.4 Pedestrian speed modeling

In this section, models to represent the speed profile of pedestrians on crosswalks are introduced. In this study, it is assumed the speed profile of each pedestrian is formed from the two travel speeds $v_1$ and $v_2$. Thus these two speeds are modeled as normally distributed and as a function of crosswalk geometry, pedestrian demand, pedestrian origin-destination and the defined pedestrian signal intervals G1, G2, G3 and PFG as shown in Figure 4.3.
Table 4.3 First half travel speed \( v_1 \) models in different pedestrian signal intervals

<table>
<thead>
<tr>
<th>Gamma Distribution</th>
<th>Parameters</th>
<th>( G1 ) and ( G2 ) ( v_1 ) N(( \mu, \sigma ))</th>
<th>( G3 ) ( v_1 ) N(( \mu, \sigma ))</th>
<th>( PFG ) ( v_1 ) N(( \mu, \sigma ))</th>
<th>Estimate (Sig.)</th>
<th>Estimate (Sig.)</th>
<th>Estimate (Sig.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>Const</td>
<td>1.347372 (0.000)</td>
<td>1.113781 (0.000)</td>
<td>2.023283 (0.000)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Crosswalk length (m)</td>
<td>0.004494 (0.002)</td>
<td>0.0221197 (0.003)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pedestrian demand* (ped./hr/m_width)</td>
<td>-0.005097 (0.000)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Const</td>
<td>0.241910 (0.000)</td>
<td>-0.0643659 (0.519)</td>
<td>0.708038 (0.000)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Crosswalk length (m)</td>
<td>0.004254 (0.000)</td>
<td>0.023111 (0.000)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pedestrian demand* (ped./hr/m_width)</td>
<td>-0.003817 (0.000)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Log likelihood</td>
<td>-113.33673</td>
<td>-113.6195</td>
<td>-48.31568</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Sample Size</td>
<td>698</td>
<td>194</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Pedestrian demand per hour per meter width of the crosswalk.

Table 4.4 Second half travel speed \( v_2 \) models in different pedestrian signal intervals

<table>
<thead>
<tr>
<th>Gamma Distribution</th>
<th>Parameters</th>
<th>( G1 ) and ( G2 ) ( v_2 ) N(( \mu, \sigma ))</th>
<th>( G3 ) ( v_2 ) N(( \mu, \sigma ))</th>
<th>( PFG ) ( v_2 ) N(( \mu, \sigma ))</th>
<th>Estimate (Sig.)</th>
<th>Estimate (Sig.)</th>
<th>Estimate (Sig.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>Const</td>
<td>0.4282726 (0.000)</td>
<td>0.510429 (0.000)</td>
<td>0.002715 (0.991)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>First half travel speed ( v_1 ) (m/sec)</td>
<td>0.727701 (0.000)</td>
<td>0.614326 (0.000)</td>
<td>0.342651 (0.000)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Crosswalk length (m)</td>
<td>-</td>
<td>-</td>
<td>.048067 (0.000)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Pedestrian demand* (ped./hr/m_width)</td>
<td>-0.002302 (0.002)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Dummy (Far-side=1, Near-side=0)</td>
<td>0.021047 (0.199)</td>
<td>0.031439 (0.462)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Const</td>
<td>0.149236 (0.000)</td>
<td>-0.030211 (0.476)</td>
<td>0.003041 (0.970)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>First half travel speed ( v_1 ) (m/sec)</td>
<td>0.113909 (0.000)</td>
<td>0.186845 (0.000)</td>
<td>0.158452 (0.001)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Crosswalk length (m)</td>
<td>-0.004377 (0.000)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Dummy (Far-side=1, Near-side=0)</td>
<td>0.049379 (0.000)</td>
<td>0.08538 (0.005)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Log likelihood</td>
<td>104.07288</td>
<td>-37.197825</td>
<td>-48.31568</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Sample Size</td>
<td>698</td>
<td>194</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Pedestrian demand per hour per meter width of the crosswalk.

Table 4.3 shows the developed first half travel speed \( v_1 \) models for different pedestrian signal intervals, while Table 4.4 shows the developed second half travel speed \( v_2 \) models. Travel speeds \( v_1 \) and \( v_2 \) during G1 and G2 are significantly affected by pedestrian demand per hour per meter width of the crosswalk which is not the case during G3 and PFG. Furthermore, it is clear that crosswalk length is one of the most significant parameters and it has a positive relationship with pedestrian travel speed. During PFG, it is difficult to clarify the significance of several parameters such as pedestrian origin-destination due to the few available samples. Thus it is necessary to collect more data to develop a reliable model.
4.3 Gap acceptance models

To be able to estimate the speed adjustments of left-turning vehicles due to pedestrians, the acceptance of gaps between crossing pedestrians by drivers needs to be modeled and quantified. In this section, the acceptance of lags and gaps between pedestrians by left-turning drivers are described. The maneuvers of left-turning traffic and pedestrians are extracted from video data by using the image processing program TrafficAnalyzer (Suzuki and Nakamura, 2006). Refer to Section 2.5 for an explanation of the methodology.

The characteristics of the observed sites are listed in Table 4.5. Collected data are classified according to the defined types of lags/gaps in Figure 2.10. The cumulative Weibull Distribution is used to fit the collected lag/gap acceptance distributions as shown in Figure 4.8. Developed models are applicable only for passenger cars, since sufficient data for heavy vehicles are not available to calibrate the models. As shown in Figure 4.8, drivers tend to accept shorter gaps of pedestrians arriving from the near-side (Type A) than from the far-side (Type B), thus highlighting the importance of the pedestrians’ crossing direction on driver behavior.

Table 4.5 Number of accepted and rejected lag/gaps of each type for observed sites

<table>
<thead>
<tr>
<th>Intersection name</th>
<th>Approach</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
<th>Type D</th>
<th>Type E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A’</td>
<td>R’</td>
<td>A’</td>
<td>R’</td>
<td>A’</td>
</tr>
<tr>
<td>今池 Imaike</td>
<td></td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>青山 Aoyama</td>
<td>北 north</td>
<td>1</td>
<td>-</td>
<td>10</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>西 west</td>
<td>2</td>
<td>0</td>
<td>5</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>川名 Kawana</td>
<td></td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>末盛通 Suemoridori</td>
<td>東 east</td>
<td>3</td>
<td>-</td>
<td>5</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>北 north</td>
<td>13</td>
<td>14</td>
<td>13</td>
<td>6</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>西 west</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>広路通 Hirojidori</td>
<td></td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>14</td>
<td>-</td>
</tr>
<tr>
<td>堀田 Horita</td>
<td>東 east</td>
<td>9</td>
<td>2</td>
<td>20</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>南 south</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>西大須 Nishiosu</td>
<td>西 west</td>
<td>6</td>
<td>4</td>
<td>25</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>太閤通り Taikodori</td>
<td>西 west</td>
<td>4</td>
<td>20</td>
<td>6</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>55</td>
<td>67</td>
<td>104</td>
<td>92</td>
<td>39</td>
</tr>
</tbody>
</table>

* A is accepted lag/gap while R is rejected lag/gap.
4.4 Path of left-turning traffic

As explained in Section 2.1, the path of turning traffic is modeled by a combination of straight, circular and Euler spiral curves. The estimated models for the curve segments which are shown in Equations (2.1), (2.2) and (2.3) are listed in Table 4.6 and Table 4.7. It is assumed that the entering spiral curve parameter $A_1$ and the exit spiral curve parameter $A_2$ are dependent on the minimum speed along the turning maneuver. Thus $V_{\text{min}}$ is modeled assuming a Normal Distribution. For detailed information refer to the first year report of the project.
Table 4.6 Results of estimated Euler spiral parameters for left-turning vehicles

<table>
<thead>
<tr>
<th>Explanatory variables</th>
<th>Parameter of entering Euler spiral curve $A_1$(m) Parameters (t-values)</th>
<th>Parameter of exit Euler spiral curve $A_2$(m) Parameters (t-values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const.</td>
<td>-1.65(-1.85)</td>
<td>2.33(2.83)</td>
</tr>
<tr>
<td>Corner radius $R_c$ (m)</td>
<td>0.334(8.73)</td>
<td>0.335(7.52)</td>
</tr>
<tr>
<td>Intersection angle <em>(degrees)</em></td>
<td>0.0404(3.61)</td>
<td>-</td>
</tr>
<tr>
<td>Heavy vehicle dummy (heavy vehicle:1, passenger car: 0)</td>
<td>-</td>
<td>2.05(2.89)</td>
</tr>
<tr>
<td>Lateral distance from shoulder to center of exit lane (m)</td>
<td>0.461(7.70)</td>
<td>1.04(15.2)</td>
</tr>
<tr>
<td>Minimum speed $V_{min}$(km/h)</td>
<td>0.369(9.04)</td>
<td>0.268(6.88)</td>
</tr>
</tbody>
</table>

Table 4.7 Results of estimated minimum radius and minimum speed for left-turning vehicles

<table>
<thead>
<tr>
<th>Explanatory variables</th>
<th>Radii of circular curve $R_{min}$(m) Parameters (t-values)</th>
<th>Minimum speed $V_{min}$(km/h) Parameters (t-values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const.</td>
<td>-6.46(-6.31)</td>
<td>1.20(0.91)</td>
</tr>
<tr>
<td>Corner radius $R_c$ (m)</td>
<td>0.390(12.9)</td>
<td>0.212(4.20)</td>
</tr>
<tr>
<td>Intersection angle <em>(degrees)</em></td>
<td>0.127(13.1)</td>
<td>0.156(11.6)</td>
</tr>
<tr>
<td>Heavy vehicle dummy (heavy vehicle:1, passenger car: 0)</td>
<td>-</td>
<td>-4.62(-5.32)</td>
</tr>
<tr>
<td>Lateral distance from shoulder to center of exit lane (m)</td>
<td>0.862(16.8)</td>
<td>0.794(9.22)</td>
</tr>
</tbody>
</table>

4.5 Speed profiles of left-turning traffic

4.5.1 Maneuver parts

Left turning traffic commonly has to yield to crossing pedestrians. If no pedestrians are present, the driver will follow an ideal speed profile. He might have to deviate from this profile if he has to react to pedestrians. Neglecting car-following behavior, which is modeled separately, and the reaction to signals, which is also modeled separately, the drivers approaching the crosswalk will have to observe pedestrians and react according to the assessment of the situation. If the driver is not sure that he can clear the crosswalk safely, he will decelerate, if necessary to a full stop. Only
once he perceives a sufficient gap in the pedestrian stream he will accelerate and clear the conflict area at the crosswalk.

To model this behavior the turning maneuver is divided into three parts as follows:

- The driver approaches the intersection and reduces the speed in order to turn safely. During this part the driver follows the ideal speed profile. This profile is determined by intersection geometry and driver characteristics.
- The driver perceives pedestrians on the crosswalk and yields to them. It is assumed that the driver reduces the speed in a way that he can come safely to a full stop in front of the crosswalk, if necessary. This deceleration is described by a stopping profile. The time when the driver changes from the ideal speed profile to the stopping profile with reference to the start of the turning maneuver is called yielding time $t_{yield}$. While the driver decelerates, he continues to observe the crosswalk and waits for an acceptable gap.
- Once the driver perceives a suitable gap in the pedestrian stream on the crosswalk, he accelerates to the desired exiting speed and, thus, clears the crosswalk. This behavior is described by a clearing profile. The time when the driver decides to pass is called passing time $t_{pass}$.

This three step process is illustrated in Figure 4.9. The driver starts the approach to the intersection at point $\text{\textcircled{1}}$. At point $\text{\textcircled{1}}$ he scans the pedestrian crosswalk for the first time and decides to yield (no suitable gap at time $A$). During each time step he re-assesses the situation at the crosswalk. This re-assessment is highlighted for point $\text{\textcircled{2}}$. Since the driver wants to safely pass as early as possible, he

![Figure 4.9 Ideal speed profile, stopping profile, and clearing profile in reaction to pedestrians](image-url)
assumes the clearing profile for the acceleration and predicts his arrival at the crosswalk to be at B. He rejects the gap available at this time and follows the stopping profile further. At point urtles the assessment leads to the acceptance of the gap at C. The driver switches to the clearing profile (passing time), passes the crosswalk at C, accelerates to the desired exiting speed and finishes the turning maneuver at point ♂.

The available gap is checked using the gap acceptance model described in Section 2.5. The driver assumes constant walking speed of the pedestrians.

Yielding time and passing time are determined by the driver reaction to pedestrians. For simplification it is assumed that the driver reacts to pedestrians once he passed the stop line. From this time on, the driver will scan the crosswalk and assess the gaps in the pedestrian stream.

It is not possible to adequately verify this simplified model without extensive driving experiments. However, the speed profiles resulting from this model can be validated with empirical data. In reality drivers will assess possible gaps in dependence of their own distance from the crosswalk. The farther they are from the crosswalk, the more uncertainty is involved in predicting the pedestrian behavior. Due to insufficient data on the effect of this uncertainty, the model will not consider the distance of the vehicle from the crosswalk.

4.5.2 Empirically derived model parameters

The basic principles of the speed of vehicles when turning at a signalized intersection have been explained in Section 2.3. The particularities of left-turning speed profiles are incorporated into the model by empirical analysis of the speed function coefficients and constraints. Table 4.8 shows the constraints for the speed equation (2.4) with the acceleration as the first derivative and their four unknowns (cf. Figure 2.4). This system of linear equations is underdetermined for the ideal speed profile (inflow and outflow) and for the clearing profile. The coefficient $c_1$ and the minimum speed $v_{min}$ are empirically modeled.

In addition to $v_{min}$, $c_{L,in}$, $c_{L,out}$, and $c_1$ of the clearing profile the position of the speed profile with reference to the path of the vehicle $x_{min}$ is empirically modeled (cf. Subsection 2.3.4). The observed behavior of vehicles reveals that these parameters are related to certain intersection characteristics, namely the intersection angle, the curb radius, the lateral distance of the vehicle in the exit, the entering speed, and the exiting speed (cf. Figure 2.2). Correlation charts with the different influencing factors are shown on the following pages. The linear trend is shown with the mean plus/minus the standard deviation indicated by dashed lines.
Table 4.8 Constraints and modeled parameters for the speed profile of left-turning vehicles

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ideal profile (inflow)</th>
<th>Ideal profile (outflow)</th>
<th>Stopping profile</th>
<th>Clearing profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>v (in)</td>
<td>( v_{\text{enter}} )</td>
<td>( v_{\min} )</td>
<td>( v_{\text{ideal}} )</td>
<td>( v_{\text{stop}} )</td>
</tr>
<tr>
<td>v (out)</td>
<td>( (v_{\min}) )</td>
<td>( v_{\text{exit}} )</td>
<td>( 0 )</td>
<td>( v_{\text{exit}} )</td>
</tr>
<tr>
<td>a (in)</td>
<td>( a_{\text{enter}} )</td>
<td>( 0 )</td>
<td>( a_{\text{ideal}} )</td>
<td>( a_{\text{stop}} )</td>
</tr>
<tr>
<td>a (out)</td>
<td>( 0 )</td>
<td>( a_{\text{exit}} )</td>
<td>( 0 )</td>
<td>( a_{\text{exit}} )</td>
</tr>
<tr>
<td>t (out)</td>
<td>( (t_{\text{min}}) )</td>
<td>( (t_{\text{exit}} - t_{\text{min}}) )</td>
<td>( (t_{\text{stop}} - t_{\text{in}}) )</td>
<td>( (t_{\text{exit}} - t_{\text{in}}) )</td>
</tr>
<tr>
<td>Degree of freedom/constraints</td>
<td>5/3</td>
<td>5/4</td>
<td>5/5</td>
<td>5/4</td>
</tr>
<tr>
<td>Modeled parameter</td>
<td>( v_{\min}, c_{1,\text{in}} )</td>
<td>( c_{1,\text{out}} )</td>
<td>( c_{1} )</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.10 Illustration of empirically modeled coefficients and constraints for the speed profile (left-turning)

The parameters are modeled as randomly distributed values. For the coefficients characterizing the random distribution, a linear combination of the most important influencing factors has been used. The coefficients are given in a table for each speed profile parameter.
The coefficient $c_1$ represents a jounce (second derivative of the acceleration). It determines the shape of the speed profile. For the inflow it is positive, for the outflow it is negative. The distribution shows a distinct positive skew. Therefore, a Gamma Distribution is chosen to represent the data as shown in Figure 4.11.

Due to the great number of potential factors influencing the coefficient $c_1$ of the ideal speed profile for left-turning vehicles, a big sample size is required to study them. Figure 4.12 indicates a moderate correlation between entering speed, the lateral position of the vehicle at the exit (related to the chosen exit lane), the intersection angle, the curb radius and the coefficient $c_{L,in}$ for the inflow. In case of the outflow coefficient $c_{L,out}$ the exiting speed and the lateral position of the vehicle in the exit appear to be important factors as shown in Figure 4.13. The chosen models are given in Table 4.9.
Figure 4.12 Correlation between several parameters and $c_{1,\text{in}}$ Coefficient for left-turning vehicles

Figure 4.13 Correlation between exiting speed, lateral exit distance and coefficient $c_{1,\text{out}}$ for left-turning vehicles
Table 4.9 Models of $c_{i,in}$ and $c_{i,out}$ coefficients for left-turning vehicles

<table>
<thead>
<tr>
<th>Gamma Distribution</th>
<th>Parameters</th>
<th>$c_{i,in}$ ~ $\Gamma(\alpha, \beta)$ Estimate (Sig.)</th>
<th>$c_{i,out}$ ~ $\Gamma(\alpha, \beta)$ Estimate (Sig.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Const</td>
<td>2.090837 (0.019)</td>
<td>1.402047 (0.013)</td>
</tr>
<tr>
<td></td>
<td>Entering speed (m/sec)</td>
<td>0.2563564 (0.000)</td>
<td>-</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Intersection angle (degrees)</td>
<td>-0.0154569 (0.046)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Corner radius (m)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Lateral exit distance (m)</td>
<td>-0.1678538 (0.006)</td>
<td>0.0633479 (0.033)</td>
</tr>
<tr>
<td></td>
<td>Exiting speed (m/sec)</td>
<td>-</td>
<td>-0.0224424 (0.623)</td>
</tr>
<tr>
<td></td>
<td>Const</td>
<td>0.0573156 (0.000)</td>
<td>0.0771912 (0.000)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Entering speed (m/sec)</td>
<td>-0.001729 (0.000)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Corner radius $R_c$ (degrees)</td>
<td>-0.001088 (0.002)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Lateral exit distance (m)</td>
<td>0.0021931 (0.022)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Exiting speed (m/sec)</td>
<td>-</td>
<td>-0.0035521 (0.004)</td>
</tr>
<tr>
<td></td>
<td>Log likelihood</td>
<td>336.43562</td>
<td>379.66862</td>
</tr>
<tr>
<td></td>
<td>Sample Size</td>
<td>202</td>
<td>188</td>
</tr>
</tbody>
</table>

Minimum speed

The distribution of observed minimum speeds follows an only slightly skewed distribution as shown in Figure 4.14. A Normal Distribution still fits the data well. The minimum speed

![Figure 4.14 The distribution of observed minimum speeds $v_{min}$ for left-turning vehicles](image-url)
potentially depends on a range of factors. Figure 4.15 indicate a correlation of entering speed, lateral position of the vehicle in the exit, curb radius, and intersection angle with the minimum speed. The chosen model is shown in Table 4.10.
The position of minimum speed $x_{\text{min}}$ is defined as the distance from the beginning of the turning path of the vehicle (first clothoid) of the vehicle path in the intersection to the point where the minimum speed $v_{\text{min}}$ occurs (cf. Subsection 2.3.4). As shown in Figure 4.16, $x_{\text{min}}$ follows a symmetric distribution; therefore, it is modeled as a Normal Distribution. It is found that intersection angle, curb radius, and lateral position of the vehicle in the exit are the most significant influencing factors as shown in Figure 4.17. The chosen model is shown in Table 4.10.

### Table 4.10 Minimum speed $v_{\text{min}}$ and position of minimum speed $x_{\text{min}}$ models for right-turning vehicles

<table>
<thead>
<tr>
<th>Gamma Distribution</th>
<th>Parameters</th>
<th>$v_{\text{min}}$ Estimate (Sig.)</th>
<th>$x_{\text{min}}$ Estimate (Sig.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Const</td>
<td>-0.3006497 (0.496)</td>
<td>1.418104 (0.516)</td>
</tr>
<tr>
<td></td>
<td>Entering speed (m/sec)</td>
<td>0.0907563 (0.003)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Corner radius $R_c$ (m)</td>
<td>0.0606657 (0.000)</td>
<td>0.5861338 (0.000)</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Intersection angle (degrees)</td>
<td>0.0386817 (0.000)</td>
<td>0.0896472 (0.000)</td>
</tr>
<tr>
<td></td>
<td>Lateral exit distance (m)</td>
<td>0.2327502 (0.000)</td>
<td>0.5774585 (0.000)</td>
</tr>
<tr>
<td></td>
<td>Heavy vehicle dummy (HV:1, PC:0)</td>
<td>-0.4964164 (0.107)</td>
<td>-</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Const</td>
<td>0.6649318 (0.000)</td>
<td>0.1351356 (0.828)</td>
</tr>
<tr>
<td></td>
<td>Lateral exit distance (m)</td>
<td>0.041912 (0.019)</td>
<td>0.3356169 (0.000)</td>
</tr>
<tr>
<td></td>
<td>Corner radius $R_c$ (m)</td>
<td>-</td>
<td>0.1443846 (0.002)</td>
</tr>
<tr>
<td></td>
<td>Log likelihood</td>
<td>-257.82707</td>
<td>-541.88456</td>
</tr>
<tr>
<td></td>
<td>Sample Size</td>
<td>202</td>
<td>199</td>
</tr>
</tbody>
</table>

**Position of minimum speed on the vehicle path**

The position of the minimum speed $x_{\text{min}}$ is defined as the distance from the beginning of the turning path of the vehicle (first clothoid) of the vehicle path in the intersection to the point where the minimum speed $v_{\text{min}}$ occurs (cf. Subsection 2.3.4). As shown in Figure 4.16, $x_{\text{min}}$ follows a symmetric distribution; therefore, it is modeled as a Normal Distribution. It is found that intersection angle, curb radius, and lateral position of the vehicle in the exit are the most significant influencing factors as shown in Figure 4.17. The chosen model is shown in Table 4.10.

---

**Figure 4.16** The distribution of observed $x_{\text{min}}$ (position of minimum speed) for left-turning vehicles

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Following the same discussion in Section 3.6, an index to evaluate the conflicts between pedestrian and left-turning vehicles is an essential requirement. Most of the previous studies use PET to assess such conflicts which means that the kinetic energy of the turning vehicle is not considered. However the speed of the vehicle and its type is an important factor in determining the severity and the damage caused by the collision. Thus, a new index which is called as Vehicle Pedestrian Index VPI is proposed for the assessment of conflicts between pedestrians and turning vehicles as shown in Equation (4.1).

\[
VPI = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 + \frac{1}{2}J\theta^2
\]

Figure 4.17 Correlation between several parameters and position of minimum speed \( x_{\text{min}} \) for left-turning vehicles

4.6 Safety Indices

Following the same discussion in Section 3.6, an index to evaluate the conflicts between pedestrian and left-turning vehicles is an essential requirement. Most of the previous studies use PET to assess such conflicts which means that the kinetic energy of the turning vehicle is not considered. However the speed of the vehicle and its type is an important factor in determining the severity and the damage caused by the collision. Thus, a new index which is called as Vehicle Pedestrian Index VPI is proposed for the assessment of conflicts between pedestrians and turning vehicles as shown in Equation (4.1).
\[ VPI = \frac{K_e}{\epsilon_{PET}} = \frac{1}{2} \mu u^2 \epsilon_{PET} \] (4.1)

Where \( m \) is the mass of the turning vehicle (kg), and \( u \) is the speed of the turning vehicle at the conflict point (m/s). VPI will be used as the output of the simulation model for the safety assessment of conflicts between pedestrian and turning vehicles at signalized intersections.
5 Simulation Development

5.1 Introduction

5.1.1 Outline and objectives

To enable a safety assessment as described in Sections 3.6 and 4.6, a simulation environment was programmed. This simulation software provides a simple framework to integrate the models for conflicts inside of intersections. The basic vehicle behavior follows the same principles as existing microscopic traffic flow simulations. Traffic generation based on OD matrices, car following behavior, different vehicle types with individual randomly distributed characteristics and simple pre-timed signal control modules enable a basic representation of the traffic flow along links between nodes.

The developed micro-simulation, however, focuses on the vehicle behavior inside of intersections. In this way the simulation goes beyond existing software. So far the start-up behavior of through traffic, the clearing behavior of right turning traffic, the turning behavior of right and left turning traffic, the reaction of left turning vehicles to pedestrians, and the passing behavior of pedestrians on crosswalks has been implemented.

Objective of the simulation is the validation and demonstration of the developed models, and, furthermore, the safety assessment of different intersection layouts and signal timings.

5.1.2 Requirements and capabilities

To address the advantages of the proposed simulation model, it is useful to compare it with the capabilities of existing simulation programs. Table 5.1 shows a comprehensive comparison between the proposed simulation program and another three popular microscopic simulation programs. The references of this comparison are Gettman and Head (2003), Jones, et al. (2004) and AIMSUN 5.1 Micro-simulator User’s manual (2006).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>VISSIM</th>
<th>AIMSUN</th>
<th>PARAMICS</th>
<th>Proposed simulation program</th>
</tr>
</thead>
<tbody>
<tr>
<td>General characteristic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphical editor</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Road systems</td>
<td>Network</td>
<td>Network</td>
<td>Network</td>
<td>Isolated intersection*</td>
</tr>
<tr>
<td>Signal timing</td>
<td>Actuated</td>
<td>Actuated</td>
<td>Actuated</td>
<td>Pre-timed*</td>
</tr>
<tr>
<td>Traffic assignment</td>
<td>Dynamic</td>
<td>Dynamic</td>
<td>Dynamic</td>
<td>Fixed*</td>
</tr>
<tr>
<td>Behavior models</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle gap acceptance model</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Feature</td>
<td>Lane changing model</td>
<td>Car following model</td>
<td>Reaction to yellow</td>
<td>Reaction to green</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>---------------------</td>
<td>---------------------</td>
<td>--------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>By driver</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

* Planned to be improved in the near future

To achieve the objectives described before, the simulation environment has to fulfill certain requirements. The major focus is the generation of safety indices for the conflicts mentioned. Therefore, the vehicle behavior inside of intersections has to be accurately simulated. Minimum requirements are as follows:

- Isolated intersection with defined geometry and layout (approach and exit lanes, curb radii, hard nose positions etc.)
- Pre-timed signal control

Data extraction:
- Road users' state exportable to file: Yes
- Conflict characteristics (Position, timing, speed of conflicting vehicles, etc.): Limited to rear-end conflicts only
- Maximum turning speed only
- By approaching speed, position of vehicle, vehicle type, intersection geometry.

Calibration and parameters:
- Update time steps can be changed: Yes
- Vehicle size: By type
- Variable headways: By vehicle type

To achieve the objectives described before, the simulation environment has to fulfill certain requirements. The major focus is the generation of safety indices for the conflicts mentioned. Therefore, the vehicle behavior inside of intersections has to be accurately simulated. Minimum requirements are as follows:

- Isolated intersection with defined geometry and layout (approach and exit lanes, curb radii, hard nose positions etc.)
- Pre-timed signal control
• Passenger cars with defined properties (dimension, desired and limiting speeds and accelerations etc.)
• Traffic demand between origin and destination lanes.

The intersection should reflect a typical layout, which has to be considered in the driver behavior models. In this way, each individual vehicle follows a unique trajectory. The trajectory is influenced by intersection characteristics, other travelers (vehicles and pedestrians), and signal control. These minimum requirements are fulfilled in the simulation.

The software, moreover, provides a flexible framework in order to easily extent the capabilities. The vehicle parameters, trajectories and safety relevant variables are recorded in standardized format for subsequent processing. To visually check and easily adjust the simulation input and output, a graphical user interface is provided.

So far the vehicles follow the randomly assigned routes from an origin lane to a destination lane (no lane changing behavior). The number, width and type of lanes can be freely chosen. Three vehicle types are already defined. In future versions, the software will be extended by further models like lane changing models and models for other then the mentioned conflict types. More complex signal control algorithms can be incorporated.

5.1.3 Simulation framework

The simulation software processes the movement of vehicles and pedestrians in a network. The network is split into roadways (detailed by lanes) and intersections (detailed by layout and geometry). The position of vehicles is further classified into functional areas. Depending on the functional area the vehicle currently passes, it reacts to specific network elements (traffic signals, intersection geometry, other vehicles or pedestrians etc.). These reactions are modeled. At each time several models can be required to accurately describe the vehicle behavior.

The network of the current version is limited to one intersection. Not all models are implemented yet. The simulation framework, however, is designed in a way that new models can easily be integrated.

5.1.4 Input and output

The simulation requires detailed information on the intersection layout (crosswalk and hard nose position, curb radius etc.) in addition to a simple network description by links and nodes only. Origin-destination matrices have to be defined with reference to entering and exiting lanes. The
simulation can be calibrated by a range of vehicle properties, which can be so far defined for three different vehicle types. The state variables of all vehicles are recorded. The state is defined by:

- ID
- Type of vehicle
- coordinates (X,Y)
- travelled distance
- speed and acceleration
- parameters of the trajectory (clothoid parameters and radius)

For clearing right-turning traffic the late exit time (LET) is recorded, for entering through traffic the starting-response time (SRT) is saved. Furthermore, the traffic signal timing is recorded.

One of the advantages of the simulation program is, that the user can track the information of running vehicles in real-time. By directly clicking on vehicles which are running on the simulation canvas, the information of the tracked vehicle is shown in a panel as shown in Figure 5.1.

![Real-time tracking system](image)

Figure 5.1 Real-time tracking system

### 5.2 Realization

#### 5.2.1 Simulation software basics

The software is implemented in the C# programming language. The system architecture of the simulation program is displayed in Figure 5.2. The four main subsystems are:
Main Graphical User Interface, which provides an intuitive mode for interacting with the users;

Simulation Calculation Engine is the “brain” of the system, it contains all the analytical models, algorithms and is responsible for processing information;

Encoding/Decoding engine which is responsible for transformation of graphical input information as well as other input data to text data and vice versa;

Data record Engine which is responsible for recording all of the simulation information for further processing and analysis.

The simulation uses an updating step of 0.1 s, which is independent of the frame rate of the animation.

5.2.2 User interaction

Graphical User Interface (GUI)

Figure 5.3 presents the main Graphical User Interface of the simulation program. It consists of the display canvas, where roadways and intersections as well as other elements are drawn and the animated traffic is shown, a menu bar, a toolbar, and a status bar.
Data storage

Data is stored in the Extensible Markup Language (XML) to provide a standardized and well structured format. In the simulation program, XMLEncoder and XMLDecoder Engines are provided for loading and saving data. Thus, all graphical objects including their characteristics and other input data will be encoded into text data and stored in XML format files. When opening an existing project, the encoded information from XML files will be decoded into graphical elements.

Vehicle and pedestrian animation

The vehicle and pedestrian animation poses high requirements on the computer. The algorithms and calculation steps in the simulation program have been optimized to avoid judder (non-smooth motion). The Time-Based Animation technique is used. The advantage of this technique is that it can maximize animation compatibility across multiple processors and the simulation step is independent of the frame rate.

5.2.3 Network elements

The program has functionalities that allow a user to quickly design an intersection and connect it to roads as well as to other elements. The major difference to existing microsimulation software is the representation of intersections in the network. Intersections are described in detail by their size, curbside corners, stop-bars, crosswalks, and signal lights (Figure 5.4). The intersection elements and other network elements are discussed in detail in the following paragraphs.
Intersections

So far the simulation is limited to isolated intersections. The intersection is connected to roadways. A corner of the intersection is defined by two roadways and connected by a circular curve with modifiable radius.

Roads

The simulation program currently supports roadways with a straight segment, which connects from a starting point to an ending point of a roadway. Each roadway consists of a constant number of lanes (so far no lane additions or subtractions). The cross section of a roadway will be determined by the number of lanes, the individual width of each lane, and the width of the raised median. The user can assign a traffic flow direction for each lane (shared or exclusive lanes). Furthermore, the length of the median can be modified, since it is an input factor for the turning models.

Stop-bar and stopping position

The user can draw a stop-bar at any position at the intersection (even inside of the intersection for right-turning vehicles that are waiting for an acceptable gap in the conflicting through traffic). The stop bar is taken as the stopping position of waiting vehicles. The user can design individual stop-bar and stopping positions for each lane of a roadway.

Traffic lights

Traffic lights display the current phase of the signal controller.
**Crosswalk**

Crosswalks are designed at intersections with a defined width. Pedestrians will be generated at both sides of crosswalks. The near-side and far-side with reference to conflicting traffic will be automatically determined depending on the distance of the origin position and the destination position of the pedestrian to the conflict area.

**Possible modifications**

After drawing connected roadways, intersections as well as other elements with default setting values, the user can easily modify the elements by directly dragging on the graphic interface. The properties of elements can also be obtained or modified by right-clicking on a particular element and selecting the required functionalities from a pop-up menu.

**5.2.4 Traffic flow elements**

**Vehicle types and sizes**

In the simulation program, so far three types of vehicles are implemented (Passenger Cars, Single Unit Trucks and Buses) as shown in Figure 5.5. The user can design the size (length and width) and certain driving characteristics (desired speed, maximum acceleration/deceleration) for each type of vehicles.

![Passenger Car, Single Unit Truck, Bus](image)

Figure 5.5 Vehicle shapes in the simulation program

The desired speeds of vehicles are randomly generated based on a Normal Distribution. When vehicles are launched a desired speed will be assigned. The free-flow vehicles incline to reach and maintain a desired speed when running.

Mean $\mu$ and standard deviation $\sigma$ depend on the vehicle type. In the simulation program the default values of $\mu$ and $\sigma$ are defined as shown in Table 5.2.
The maximum acceleration rate (for a vehicle starting from zero speed) and maximum deceleration rate are defined as in Table 5.3 based on AASHTO 2004 and FHWA-HRT-04-040.

### Table 5.3 Acceleration/Deceleration characteristics of vehicles

<table>
<thead>
<tr>
<th>Type of vehicle</th>
<th>Max Acc</th>
<th>Max Dec</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>3.05 (10ft/s²)</td>
<td>3.6 (12ft/s²)</td>
<td>m/sec²</td>
</tr>
<tr>
<td>Heavy vehicle</td>
<td>1.50 (5ft/s²)</td>
<td>3.6 (12ft/s²)</td>
<td>m/sec²</td>
</tr>
</tbody>
</table>

**Pedestrians**

A simulated pedestrian has a shape as shown in Figure 5.6. Sizes of simulated pedestrians are determined by actual scale.

![Figure 5.6 Shape of a pedestrian in the simulation program](image)

**Traffic Demand**

Origin-Destination (O-D) trip tables represent the demand between entry/exit-lane pairs. As shown in Figure 5.7, the origins are initial points of input lanes (marked by capital characters) of a connected roadway and the destinations are the end points of output lanes of other connected roadway. In the simulation program, a trip from the origin to the destination of a vehicle is assumed to be fixed. Vehicles will be generated from the origin source and they cannot change the lane when running toward to the destination.
5.2.5 Signal control elements

Traffic signal control follows a pre-timed four phase control most common in Japan with lagging protected right turn. Vehicle signals follow a green-yellow-red sequence. Pedestrian lights have a green, flashing green and red sequence. Figure 5.8 presents an example of signal groups for an intersection, while Figure 5.9 shows phase modeling of the same intersection.

Vehicles are assumed not to react to signal lights when farther than 200 m upstream of the stop-bar. This distance provides enough time for approaching vehicles with speed lower than 70 km/h to join a queue before the stop-bars of the intersection.

\[ \begin{align*} 
G & \text{ green time (sec)}; \\
Y & \text{ yellow time (sec)}; \\
AR & \text{ all Red time (sec)}; \\
PG & \text{ pedestrian green time (sec)}; \\
PF & \text{ pedestrian flashing time (sec)}; \\
C & \text{ cycle length (sec)}.
\end{align*} \]

Note: Phase 1, 3, 4 and 6 are vehicle phase; Phase 2 and 5 are pedestrian phases.

Figure 5.8 Example of signal groups of an intersection
5.3 Model integration

5.3.1 Overview

The simulation is focused on two types of conflicts so far: conflicts of right turning vehicles with cross traffic, and conflicts of left-turning traffic with pedestrians. The models underlying the simulation of these conflicts have been explained in the last sections of this report.

The right-turning and through traffic conflicts occur when the last clearing vehicle of the right turn phase clears the intersection and the first entering vehicle of go-through phase enters the intersection as shown in Figure 5.10. Behavior models of the last clearing right turning vehicle are necessary for examining this type of conflict that include stop/go decision at the onset of yellow, turning path and turning speed. Crucial models for the first entering go-through vehicles are startup respond time (SRT) and entering acceleration rate. In addition to implement the simulation program, other models like car following models are necessary.
The second type of conflict is left-turning traffic conflicting with pedestrians at crosswalks as shown in Figure 5.11. For this conflict a gap acceptance model which can explain the decision-making procedure when left-turning vehicles approach the crosswalk is developed. Other models that are necessary for examining this conflict are listed in Figure 5.11.

5.3.2 Traffic generation and link flow

Vehicle and pedestrian arrivals

Random arrivals of vehicles and pedestrians are assumed. Their headways, thus, conform to a negative exponential distribution (Gerlough and Huber, 1975) as shown in Equation (5.1).
\[ f(h \geq t) = e^{-\left(\frac{t-h_{\text{min}}}{H-h_{\text{min}}}\right)} \]  

(5.1)

where \( h \) is the headway (s); \( t \) is a time interval (s); \( H \) is the average headway (s); \( h_{\text{min}} \) is the minimum headway (s), \( h_{\text{min}} \) is 0 for pedestrian flows and 1s~1.2 s for vehicles flows.

**Lane choice**

So far the chosen lanes are determined by the OD matrix. When a vehicle enters the simulation, its route is defined by the randomly assigned origin and destination lane.

**Car following behavior**

The car-following model is an important sub model used in the simulation program. It shows how each driver responds to the surrounding traffic. In this simulation program, the Intelligent-Driver Model (IDM) (Martin Treiber 2000) is used to simulate the longitudinal dynamics. According to the model, the acceleration or deceleration rate of a vehicle depends on its own speed, and on the speed and relative position of the leading vehicle immediately ahead of it. The following equation shows the acceleration/deceleration rate of a vehicle at time \( t \):

\[
\frac{dv}{dt} = a \left[ 1 - \left( \frac{v}{v_o} \right)^\delta - \left( \frac{s^*}{s} \right)^2 \right] 
\]  

(5.2)

\[
s^* = s_o + \left( vT + \frac{v\Delta v}{2\sqrt{ab}} \right) 
\]  

(5.3)

where \( v_o \) is the desired speed (m/sec); \( T \) is the desired safety time headway (sec); \( a \) is the maximum acceleration rate (m/sec\(^2\)); \( b \) is the maximum deceleration rate (m/sec\(^2\)); \( s_o \) is minimum bumper-to-bumper distance to the front vehicle (m); \( s \) is the current bumper-to-bumper distance to the front vehicle (m) and \( \delta \) is an acceleration exponent which indicates how the vehicle increases speed.

Usually for enhancing startup behavior when \( \delta > 1 \); \( s \) is estimated as \( \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \) with \( P_1(x_1,y_1) \) as the middle point of the head bumper of the following vehicle and \( P_2(x_2,y_2) \) as the middle point of the rear bumper of the leading vehicle. For a free-flow vehicle, the acceleration rate is given by Equation (5.4). The used default values of the car-following model parameters as shown in Table 5.4.

\[
\frac{dv}{dt} = a \left[ 1 - \left( \frac{v}{v_o} \right)^\delta \right] 
\]  

(5.4)
Table 5.4 Default values of Car-following model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Passenger car</th>
<th>Heavy vehicle</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_0 )</td>
<td>NormalDis (45,5)</td>
<td>NormalDis (40,5)</td>
<td>m/sec</td>
</tr>
<tr>
<td>( T )</td>
<td>1.0</td>
<td>1.2</td>
<td>sec</td>
</tr>
<tr>
<td>( s_0 )</td>
<td>2.0</td>
<td>3.0</td>
<td>m</td>
</tr>
<tr>
<td>( a )</td>
<td>3.05 (10 ft/sec(^2))</td>
<td>3.6 (12 ft/sec(^2))</td>
<td>m/sec(^2)</td>
</tr>
<tr>
<td>( b )</td>
<td>1.50 (5 ft/sec(^2))</td>
<td>3.6 (12 ft/sec(^2))</td>
<td>m/sec(^2)</td>
</tr>
<tr>
<td>( \delta )</td>
<td>4</td>
<td>4</td>
<td>-</td>
</tr>
</tbody>
</table>

5.3.3 Reaction to traffic signals

**Stop/go models**

When approaching the intersection at the onset of yellow, the driver has to meet a stop/go decision. The decision of simulated vehicles is estimated based on the results of a stop/go model. If the distance is not far enough to comfortably decelerate in time, the driver will pass. The reaction to the signal of the following vehicles depends on the decision of the leading vehicle. Only if the leading vehicle decides to pass, the following vehicle will meet an independent decision as if it would be the leading vehicle.

The stop/go decision model is developed for through and right turning traffic only. For left turning vehicles, the stop/go decision depends on the minimum distance to stop at the stop-bar only.

**SRT models of entering vehicles**

So far, SRT models are developed for the through traffic only, for right-turning and left-turning traffic a fixed value of \( SRT = 0.7 \) s is assumed.

For through turning traffic, the SRT is calculated five seconds before the signal changes to green, because of the SRT distribution. Due to the model, SRT depends on the Late Exit Time (LET) of the last clearing vehicle of right-turning traffic (cf. Section 3.5).

The last clearing vehicle of right turning traffic is predicted based on the stop/go decision at the onset of yellow. If the last clearing vehicle enters the intersection (passes the stop line) during the green time, the exit is not late. In this case, LET is set to zero. The SRT distribution will be generated based on this zero LET.

In cases when the last clearing vehicle passes after the onset of yellow, LET will be predicted based on the ideal speed and the distance to the conflict point with through traffic. Because the last
clearing vehicle usually is not a leading vehicle, the real speed of the vehicle depends on the car following model. This behavior is not yet considered in the SRT model.

5.3.4 Gap acceptance models

The gap acceptance in the pedestrian stream on the crosswalk is part of the left-turning traffic models (cf. Chapter 4). The gap acceptance of right-turning traffic concerning the opposing traffic during the permitted phase has not been developed yet. In the simulation program it is assumed that right turning vehicles reject all gaps during the permitted phase.

5.3.5 Entering acceleration rate of entering vehicles

The entering acceleration rate is the acceleration rate of the first vehicle entering the intersection when green starts until it passes the conflict point with the cross traffic.

The entering acceleration model is developed for through traffic only. For right-turning traffic and left-turning traffic, the acceleration rate of entering vehicles is given by Equation (5.4). According to the acceleration rate model of through traffic, the acceleration rate of entering vehicle depends on the SRT. Therefore, it is calculated after calculating SRT.

5.3.6 Paths of turning vehicles in the intersection

The simulation uses models for the path of right-turning and left-turning vehicles (cf. Sections 3.3 and 4.4). The path is determined before the vehicle enters the intersection. This path is taken as fixed and does not change during the turning maneuver. Before the turning-vehicle enters the intersection, the driver determines a target lane (based on the OD route) on the downstream roadway. The path is generated based on this exit lane. As an example, Figure 5.12 shows the turning paths of right turning and left turning vehicles when entering the intersection.

For through traffic it is assumed that vehicles use the same lane on the intersection exit without changing lanes while crossing the intersection.
5.3.7 Speed of vehicles

In the simulation program, three general scenarios are classified in order to determine the speed profile of vehicles. The scenarios are classified based on the movement direction of vehicles as go-through, turning left and turning right vehicles. For each direction, the whole trip of vehicles from origin to destination is divided into three segments as shown in Figure 5.13: lane moving, approaching intersection, crossing intersection (or entering intersection).

Figure 5.13 Running segments of vehicles

Vehicles are considered as moving on lanes when the distance to the stop-bar of an intersection is greater than 200 m. At lane moving segments, speeds of all vehicles are determined based on the
car following behavior as shown in Equations (5.2) and (5.4). During the approach they react to the traffic signal. Vehicles are considered as crossing the intersection when they passed the stop-bar.

**Through vehicles**

1. **Approaching intersection:** In this segment, vehicles both react to the traffic signal and to the surrounding traffic. If the vehicle crosses during green, the speed choice behavior is the same with vehicles that are running on the lane moving segment. If the vehicles react to the yellow or red light, the speed depends on the order of vehicles as shown in Figure 5.14. For the first approaching vehicle (number 1) as shown in Figure 5.14, the speed choice behavior depends on the signal timing and stop/go decision. The acceleration rate of the vehicle will be calculated as in Equation (5.5)

\[
a = -\frac{v^2}{2d}
\]  

(5.5)

where \(a\) is the acceleration rate of the vehicle (\(m/sec^2\)); \(v\) is the speed of the vehicle (\(m/sec\)) and \(d\) is the distance to the stop-bar (\(m\)). Otherwise if the vehicle chooses to pass, the acceleration rate is calculated by Equation (5.4).

For the vehicle number \(i\), the speed choice behavior depends on the signal timing and the decision of the vehicle number \(i-1\). When vehicle number \(i-1\) chooses to stop, the vehicle number \(i\) automatically follows the vehicle number \(i-1\) by car following model. If the vehicle number \(i-1\) chooses to go, the vehicle number \(i\) will meet its own stop/go decision. If vehicle number \(i\) chooses to stop, the acceleration rate calculated by Equation (5.5) will be applied. Otherwise vehicle number \(i\) will follow the vehicle number \(i-1\) as in the car following model.

Figure 5.14 Through vehicles are running at the approaching segments
2. **Entering segments**: For the first entering vehicle at the beginning of green; the speed of the vehicle depends on the start-up behavior. The start-up behavior which is modeled in this project includes the start-up response time (SRT) and the entering acceleration rate. After the SRT, the first entering vehicle will accelerate with the entering acceleration rate. The vehicle will use this acceleration rate until it passed through the conflict area with right turning traffic of the opposite phase. After that, the entering vehicle will use the acceleration rate as shown in Equation (5.4). For other vehicles, the speed behavior is the same behavior with vehicles at lane moving segments.

**Right-turning vehicles**

1. **Approaching intersection**: In this segment vehicles prepare to turn as shown in Figure 5.15. An ideal speed profile is generated when vehicles start running at this segment as described in Section 2.3. The speed profile model is developed for free flow vehicles. It is necessary to distinguish between free flow vehicles and vehicles running in a platoon. Assuming a threshold of 3 s of headway between vehicles (HCM 2000) is used to distinguish between free flow vehicles and in-platoon vehicles. For in-platoon vehicles and vehicles with a speed lower than the minimum speed \( v_{\text{min}} \), the speed choice behavior is the same with through vehicles at the same segment. For free flow vehicles which have a speed greater than \( v_{\text{min}} \), ideal speeds will be applied.

![Figure 5.15 Right turning vehicles are running at the approaching segments](image)

2. **Entering segments**: For the first entering vehicle at the onset of green; the speed of the vehicle depends on the start-up behavior. However, start-up behavior for right turning vehicles has not been developed yet. In this case, SRT is assumed as \( 0.7 \text{ s} \). The first entering vehicle will use an acceleration rate calculated as in Equation (5.4). For other vehicles, the speed depends on which type of speed model they use before entering the intersection. They will continue using the speed model they used in the approaching segment.
Left-turning vehicles

1. **Approaching segment:** In this segment, left turning vehicles behave like the right turning vehicles.

2. **Entering segment:** In this segment, left turning vehicles react to pedestrians at the crosswalk as shown in Figure 5.11. Three types of speed profile models are developed as described in Subsection 4.5.1 and illustrated in Figure 4.9 (ideal speed profile, clearing profile and stopping profile). For left turning vehicles approaching the crosswalk, the speed choice depends on the gap acceptance model (Section 4.3). The loop outlined in Figure 5.16 and described in detail in Section 4.5 will be applied with a decision update interval of 0.5 s until the vehicle passed the crosswalk. In case vehicles reject all gaps until they reach the crosswalk, they will stop and wait at the crosswalk until an accepted gap appears. When an acceptable gap becomes available, drivers will use the acceleration rate estimated by Equation (5.4) to pass through the crosswalk.

![Figure 5.16 Speed choice algorithm of left turning vehicles approaching crosswalks](image)

**Pedestrian movement models**

Due to the high complexity of pedestrian behavior, so far only a simplified model is implemented for pedestrians crossing the crosswalk. It is assumed that pedestrians do not change their direction while crossing. The origin and destination positions of pedestrians are randomly generated. A simplified model is used to reflect the effect of signal timing, crosswalk length and pedestrian
direction of movement on pedestrian speed while crossing. The detailed information about these models is presented in Subsection 4.2.4.
6 Simulation Validation and Case Study

6.1 Overview

In order to verify that the simulation is working reasonably, a case study is conducted. The simulation output related to the models not yet validated and related to safety is compared to observed data. The case study also serves as a platform to highlight the potential of the safety assessment approach. Nishi-osu (西大須) intersection in Nagoya is selected for the case study. Table 6.1 shows the layout of Nishi-osu intersection and the operational characteristics.

Table 6.1 The characteristics of Nishi-osu intersection in Nagoya City

<table>
<thead>
<tr>
<th>Approach</th>
<th>Observation times (Shooting hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9:00<del>12:00 (8:45</del>12:30)</td>
</tr>
<tr>
<td><strong>East</strong></td>
<td></td>
</tr>
<tr>
<td><strong>West</strong></td>
<td>●</td>
</tr>
<tr>
<td><strong>South</strong></td>
<td>●</td>
</tr>
<tr>
<td><strong>North</strong></td>
<td>●</td>
</tr>
</tbody>
</table>

Note: ● Analyzed item
Table 6.2 Observed demands of the analyzed movements at Nishi-osu Intersection

<table>
<thead>
<tr>
<th>Intersection</th>
<th>Approach</th>
<th>Vehicular Traffic volume veh/lane/hr</th>
<th>Pedestrians demand ped/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Through</td>
<td>Left turn</td>
</tr>
<tr>
<td>Nishi-osu</td>
<td>North</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>454</td>
<td>284</td>
</tr>
<tr>
<td></td>
<td>South</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This site is characterized by a significant number of collisions, especially between pedestrians and left-turning vehicles. Data was collected at three approaches of the intersection. Collected data includes pedestrian maneuver data, turning and through traffic maneuver data.

The simulation program is calibrated using the observed vehicle and pedestrian demands for the analyzed movements as shown in Table 6.2. Pedestrian demand in the north approach refers to the pedestrians who use the crosswalk in the north approach.

The geometric layout of Nishi-osu Intersection and its representation in the simulation is shown in Figure 6.1.

![Aerial photo](image1.jpg) ![Representation of the intersection in the simulation](image2.jpg)

Figure 6.1 Photos of Nishi-osu intersection in reality and in the simulation program
6.2 Car following model

6.2.1 Introduction

Car following models are one of the essential models in the traffic simulation environments. These models are complicated and validating them requires a lot of empirical data. In this part, a simple calibration and verification process is conducted for the car-following model integrated into the simulation, the Intelligent-Driver Model (IDM).

6.2.2 Calibration methodology

**Step 1:** Calibration parameters:

The car following behavior can be presented by time headway and speed of vehicles. In this study, the queue discharge headway and queue discharge speed at the stop line are used as calibration parameters. Queue discharge headway \( (\text{sec}) \) is defined as the time difference between two consecutive vehicles in a platoon passing the stop line of an intersection while queue discharge speed \( (\text{m/sec}) \) is the departure speed at the stop line during the saturated part of the green period (Akcelik 1999). Initially, the parameters of the Intelligent-Driver Model (IDM) are set to default values as shown in Table 5.4.

**Step 2:** Data collection:

Due to the limited data only one site is selected for calibration and verification this time. The selected site is the second through lane (determined from the edge of the sidewalk) of the west approach of Nishi-ou Intersection. Signal timing and traffic characteristics of Nishi-ou intersection are described in Table 6.1 and Table 6.2. Observed queue discharged headways and queue discharged speeds of queued vehicles at the stop-line is collected by using the image processing program TrafficAnalyzer (Suzuki and Nakamura, 2006).

**Step 3:** Adjustment and verification:

By comparing observed data with estimated results (using default values), the parameters of the car following model are tuned. These parameters are assumed as fixed values or follow a normal distribution as shown in Table 6.3. To calibrate all these parameters, a lot of empirical data is necessary, however available data is limited, thus the parameter of acceleration exponent \( (\delta) \) is chosen to tune the car following model IDM. The parameter of acceleration exponent \( (\delta) \) is one of the most significant ones since it defines how the vehicles react to other vehicles in front of them or in other words it shows how vehicles adjusted their acceleration rate while running.
Table 6.3 Adjusted factors of car following model (IDM model)

<table>
<thead>
<tr>
<th>No</th>
<th>Parameters</th>
<th>Meaning</th>
<th>Passenger Car</th>
<th>Heavy vehicle (Bus and SUT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(v_0 \text{(km/h)})</td>
<td>Desired speed</td>
<td>Normal Dis. (45,5.0)</td>
<td>Normal Dis. (40,5.0)</td>
</tr>
<tr>
<td>2</td>
<td>(T \text{(sec)})</td>
<td>Minimum time headway</td>
<td>1</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>(s_0 \text{(m)})</td>
<td>Minimum bumper-to-bumper distance to front of vehicle</td>
<td>Normal Dis. (2,0,1.0) (s_0 \geq 1.0)</td>
<td>Normal Dis. (3,0,1.0) (s_0 \geq 2.0)</td>
</tr>
<tr>
<td>4</td>
<td>(a \text{(m/sec}^2))</td>
<td>Maximum acceleration</td>
<td>Normal Dis. (2.5,0.2)</td>
<td>Normal Dis. (1.25,0.1)</td>
</tr>
<tr>
<td>5</td>
<td>(b \text{(m/sec}^2))</td>
<td>Maximum deceleration</td>
<td>-3.6</td>
<td>-3.6</td>
</tr>
<tr>
<td>6</td>
<td>(\delta \text{(-)})</td>
<td>Acceleration exponent</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

If the parameter of acceleration exponent (\(\delta\)) is equal to one, the change in acceleration rate is constant as shown in Figure 6.2. It is concluded that \(\delta\) need to be more than one to enhance startup behavior as shown in Figure 6.2.

![Figure 6.2 Changing of acceleration rate with different values of parameter of acceleration exponent parameter (\(\delta\): delta)](image_url)

### 6.2.3 Verification

Figure 6.3 compares observed and simulated discharge headways at the second through lane (determined from the edge of the sidewalk) of the west approach of Nishi-osu Intersection. The observed average discharge headway is about 1.83 sec (calculated from the 5th vehicle, passenger cars only) while average simulated discharge headway is about 1.81 sec. Additionally, simulated discharge speeds increase after green start following the same tendency of observed discharge speeds as shown in Figure 6.4. Moreover the estimated discharge speeds match well the observed ones. To provide a better view of the performance of the used car following model, the time-space...
diagram of a simulated platoon of vehicles is presented in Figure 6.5. It is clear that following vehicles behave reasonably by keeping a safe distance to the leading ones.

Figure 6.3 Comparison of observed and estimated discharge headway at the stop line of the west approach of Nishi-osu intersections

Figure 6.4 Comparison of observed and estimated discharge speed at the stop line of the west approach of Nishi-osu intersections
6.3 Conflicts between clearing right-turning traffic with starting through traffic

The model for the path of turning vehicles has already been calibrated and validated in the first report. Here the focus is on safety relevant properties of the paths in the context of the simulation. One important parameter is the lateral distribution of the paths at crucial locations. So far the model assumes the vehicle to enter and exit the intersection in the middle of the respective lane. In future versions this lateral entering and exiting position will be randomly modeled to reflect better the reality.

Figure 6.6 shows the distribution of observed and simulated paths of right-turning vehicles at the north approach of Nishi-osu Intersection. The lateral path density distribution (D.D.) and the lateral cumulative distribution (C.D.) at three cross-sections along the turning paths are presented in Figure 6.6. The density and cumulative distributions are drawn in an interval of 0.5 m. The distributions of simulated and observed paths are similar in section ②. The deviation near the entry and exit are due to the simplified assumption of the lateral entering and exiting position of the vehicles. The sample size of the observed paths is small, thus collecting more data is necessary to provide a more reliable validation.
To test how the simulation presents the conflict between clearing right-turning vehicles and starting through traffic, comparisons between observed and simulated late exit time LET, start-up response time SRT and post encroachment time PET are presented. These times depend largely on the speed of the turning vehicles.

Figure 6.7 presents the simulated speed profiles of free flowing turning vehicles. As in reality (Figure 2.3) vehicles reach their minimum speed between the stop line and the downstream crosswalk.
Figure 6.8 shows the distribution of observed and simulated late exit times LETs of clearing right-turning vehicles at the north and south approaches of Nishi-osu Intersection. By conducting significance test, it is concluded that the mean of the observed and simulated LET distributions are not significantly different at the 95% confidence interval.

Figure 6.8 Comparison between observed and simulated late exit times LETs of clearing right-turning vehicles at the north and south approaches of Nishi-osu Intersection

As presented in Chapter 3, the start-up response time of through traffic is affected by the clearing behavior of right-turning vehicles. This interaction is quantitatively modeled and implemented...
inside the simulation. Figure 6.9 presents the distributions of observed and simulated start-up response times. By conducting significance test, it is concluded that the mean of the observed and simulated distributions are not significantly different at 95% confidence interval.

![Figure 6.9 Comparison between observed and simulated start-up response times SRTs of starting through vehicles at the west approach of Nishi-osu Intersection](image)

Since the main objective behind developing the microscopic simulation model is the safety assessment, it is necessary to verify that the interaction between different conflicting movements is reasonably represented. In the current project, however, only a small number of samples could be validated. Figure 6.10 presents a comparison between observed and simulated Post Encroachment Times PETs of the conflict between right turning vehicles from the north and south approaches of Nishi-osu intersection with the through vehicles from the west approach of the same intersection for an observation interval of two hours. Though by conducting significance test, the means of the observed and simulated distributions for both conflicts are significantly different at 95% confidence interval due to the small sample size, the distributions cover a similar range. The simplifications used in the current version of the simulation have to be mitigated for further improvement of the results.
Conflicts between left-turning traffic with pedestrians

To verify the performance of the path model for left-turning vehicles, Figure 6.11 and Figure 6.12 compare the distributions of observed and simulated paths of left-turning passenger cars and heavy vehicles at the west approach of Nishi-osu Intersection. The lateral path density distribution (D.D.) and the lateral cumulative distribution (C.D.) at three cross-sections along the turning paths are presented in Figure 6.11 and Figure 6.12. The density and cumulative distributions are drawn in an interval of 0.5 starting from the curb of the intersection. It’s clear that the distributions of simulated and observed paths of passenger cars are quite similar and they have the same tendency.

The difference is mainly referred to the assumption that the exiting position of the vehicles is in the centerline of the lane while observations show that the exit positions are widely distributed throughout each exit lane. This assumption affects the parameters of the estimated paths. Thus incorporating a lateral exit position model in the simulation will significantly improve the distribution of estimated paths.

6.4 Conflicts between left-turning traffic with pedestrians

Figure 6.10 Comparison between observed and simulated PETs of the conflict between through traffic from the west approach of Nishi-osu intersection and right-turners

a) With right-turners from the north approach

b) With right-turners from the south approach
Regarding heavy vehicles, it is important to note that the sample size of the observed paths for the verification is very small; this might be the reason why simulated paths are significantly different than observed ones at 95% confidence interval as shown in Figure 6.12. Furthermore, the assumption of lateral exiting position contributes to the differences as well.

To test how the simulation presents the conflict between left-turning vehicles and pedestrians, the speed profiles of free-flow, stopping and yielding left-turning vehicles are presented in Figure 6.13. Stopping and yielding profiles reflect the interaction with pedestrians. Generally, generated speed profiles are reasonable. However, when analyzing observed profiles it can be seen that under certain circumstances driver behavior follows more complex patterns as highlighted in Figure 6.14 and Figure 6.15. While the respective right patterns are well represented by the assumed speed profiles and decision making processes, the respective left patterns show stages with different acceleration rates (slight deceleration possibly due to some uncertainty of the driver on whether to proceed or to stop, followed by higher deceleration). These more complex patterns have to be incorporated into future versions of the simulation.

Figure 6.11 Comparison between observed and simulated paths of left-turning passenger cars at the west approach of Nishi-osu Intersection

Figure 6.12 Observed trajectory of Passenger Cars (P.C.) Simulated Trajectory of Passenger Cars (P.C.)

Figure 6.13 Observed trajectory of Passenger Cars (P.C.) Simulated Trajectory of Passenger Cars (P.C.)

Figure 6.14 Observed trajectory of Passenger Cars (P.C.) Simulated Trajectory of Passenger Cars (P.C.)

Figure 6.15 Observed trajectory of Passenger Cars (P.C.) Simulated Trajectory of Passenger Cars (P.C.)
Figure 6.12 Comparison between observed and simulated paths of left-turning heavy vehicles at the west approach of Nishi-osu Intersection

Figure 6.13 Simulated speed profiles of left-turning vehicles at the west approach of Nishi-osu Intersection
6.5 Sensitivity analysis

To demonstrate the potential of the developed simulation model, the effects of modifying the geometric layout of Nishi-osu intersection towards compact design upon Angle Collision Index ACI is analyzed. Figure 6.16 shows the layout plans for two scenarios; Scenario 1 is the existing geometric layout while Scenario 2 is a proposed compact layout.
In the case of a compact layout (Scenario 2) as shown in Figure 6.16b, it is advisable to modify the signal timing parameters. The all-red interval is reduced from 5 s to 3 s. By using the vehicle demands in Table 6.2, the simulation is run for three hours for each scenario defined in Figure 6.16. The Angle Collision Index (Section 3.6) is estimated for both scenarios. To calculate the ACI, the masses of the conflicting vehicles are assumed as 1500 kg (standard weight of a passenger car). With the Post Encroachment Time PET in the unit of seconds and the vehicle speed in m/s Equation (3.5) can be used to calculate the ACI.

Figure 6.17 shows the distributions of ACI for the two conflicts between through traffic from west approach and the right-turners from the north approach (Figure 6.17a)) and the south approach (Figure 6.17b) of Nishi-osu intersection for different vehicle speeds. It is important to note that the value of ACI is estimated based on Equation (3.5) by using the speeds of the conflicting vehicles and the Post Encroachment Time PET. However ACI is very sensitive to PET, thus most of the very high values of ACI correspond to very small PET values.

Figure 6.17 shows that the number of conflicts, particularly the number of severe conflicts (high values of ACI), is reduced by implementing the compact geometric layout (Scenario 2). The compact layout, hence, improves the safety appreciably. Due to the higher demand of right-turning traffic from the south as compared to right-turning vehicles from the north, the number of conflicts between through traffic and right-turners from the north approach (Figure 6.17a) is smaller than that of the conflicts with right-turners from the south approach (Figure 6.17b). However, the conflicts between right-turning vehicles from the north and through traffic from the west are more...
severe due to the adverse angles (Figure 6.17a) and the shorter distance from the stop line to the conflict area as shown in Figure 6.17a).

A distinct change from Scenario 1 to Scenario 2 can also be recognized for the conflicts of left-turning vehicles with pedestrians as underlined by the Vehicle Pedestrian Index (VPI). This index incorporates both the likeliness of conflicts (expressed by the post-encroachment time) and their severity (expressed by the kinetic energy of the vehicle). The compact intersection (Scenario 2) leads to a reduction of the severity and in most cases also the frequency of conflicts as is highlighted in Figure 6.18. Only for gap type E (Figure 2.10 shows the defined lags/gaps types) no significant improvement can be seen, and for gap type B the situation slightly deteriorates.

Another result is the severity of the conflicts as compared between the different gap types. Gaps with individual pedestrians arriving from one side only (type A and type B) are distinctly more severe than the other types, where more than one pedestrian is involved (mind the different scale of the y-Axis). This might indicate that drivers behave more cautious when several pedestrians are visible on the crosswalk.

Figure 6.17 Comparison of ACI for the conflict between through traffic and right-turners at Nishi-osu intersection for the two geometric layout scenarios
Figure 6.18 Comparison of VPI for the conflict between left-turning traffic and pedestrians at Nishi-osu intersection for the two geometric layout scenarios.
7 Conclusions and Outlook

7.1 Conclusions

The improvement of safety at signalized intersections still poses a challenge to authorities and traffic engineers. So far the safety assessment is mainly based on behavioral and accident analysis. An a priori evaluation of alternative layouts, regulations and signal control regimes before their implementation is, thus, not possible. This project aimed at overcoming this limitation by developing a microscopic simulation tool incorporating models for the driving behavior inside signalized intersections.

For clearing right-turning vehicles and the conflict with entering through-traffic and for left-turning traffic and the conflict with pedestrians detailed models have been developed, calibrated and verified, that not only give a realistic representation of the traffic flow, they are also sensitive to intersection geometry and signal control. These two conflicts have been identified as the most frequent conflict types at signalized intersections.

The models and their sub-models have been incorporated into a microscopic simulation tool. The software provides an intuitive user interface for the simulation of isolated intersections. Traffic demand as a lane based origin-destination matrix and the intersection geometry including curb radii, position of the hard nose, and crosswalk widths are the input data. The simulation outputs vehicle trajectories and several safety indices like post-encroachment time (PET).

For the safety assessment of the mentioned conflicts, two new safety indices have been proposed (Angle Collision Index, ACI, and Vehicle Pedestrian Index, VPI), which incorporate not only the conflict probability, but also the likely severity based on kinematic concepts.

A case study illustrates the potency of the new tool. Though the focus is yet limited to only two conflict types and many simplifications have yet to be avoided, the project underlines the potential of this new research approach to the safety assessment of signalized intersections.

7.2 Outlook

The developed models and their realization in a simulation software proves the validity of the new approach to the safety assessment of signalized intersections. However, the achievements can only be seen as a starting point for further research. Four areas for improvement have to be highlighted:

- Consideration of more conflict types, namely angle collisions of right-turning vehicles with opposing traffic and with pedestrians.
• Calibration and improvement of the stop-go decision, gap acceptance, and start-up behavior models for all possible movements in intersections (left-turning, right-turning, and through traffic).
• Improvement of existing models by collecting more data to increase the sample size and get more reliable results for the impact of different factors on the model parameters.
• More realistic and flexible pedestrian behavior modeling.

Figure 7.1 illustrates the major models and conflict types which have not yet been developed.

Figure 7.1 Illustration of models and conflict types which need further attention
The simulation tool proved to be a flexible base for the incorporation of further models. As compared to existing micro-simulation software, the developed tool offers a much more detailed representation of traffic flow at intersections. As an overall traffic flow simulator in networks it will remain, of course, only a test platform. Some simplifications and limitations, nevertheless, can be overcome in future versions: the limitation to an isolated intersection, the neglect of lane changing behavior, the restriction of the number of vehicle types, to name a few.

A long term perspective will be the incorporation not only of realistically modeled pedestrians in the intersection area, but also of bicycles and motorbikes and the interaction of them with each other. The models will be provided for the inclusion in existing micro-simulation tools to combine the strengths of existing and the newly developed tools.
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