MODELING SPEED PROFILES OF TURNING VEHICLES AT SIGNALIZED INTERSECTIONS

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ABSTRACT

Turning vehicles need special attention in the context of the safety evaluation and improvement of signalized intersections. So far the safety assessment of intersections is mainly based on individual accident and conflict analyses. It might be possible in the future to complement these analyses with microscopic simulations. An important step into this direction is the modeling of speed profiles of turning vehicles. For a conflict analysis at the planning stage, these speed profiles with their stochastic character have to be predicted to assess different intersection layouts and signal settings and their impact on the likelihood and severity of conflicts. By using empirical data of vehicle trajectories collected at signalized intersections in Japan, a model is developed and presented, which provides stochastic speed profiles of free-flowing left- and right-turning vehicles. The speed profiles are sensitive to intersection layout and the vehicle speed and position at the beginning and ending of the maneuver. This model can be complemented by models reflecting the reaction to pedestrians, traffic signals, and other vehicles, which are beyond the scope of this paper, to provide a general framework for the generation of speed profiles of turning vehicles.

Keywords: Safety assessment, signalized intersections, simulation, speed profile, trajectory

INTRODUCTION

Background

Accident data reveals that turning vehicles are involved in most of the accidents at signalized intersections. To improve the safety of signalized intersections it is consequently of primary importance to study and predict the behavior of turning vehicles. Safety improvements of intersections are so far based on experience and ex-post assessments. A major achievement would be to enable engineers to conduct ex-ante assessments at the planning stage. Simulation tools are the means to realize such an assessment. Existing simulation software, however, simplifies the traffic flow inside of intersections to an extent that safety assessments are not reliable. Turning radii are oriented at the intersection geometry only, the reaction to signals and pedestrians is often modeled as a deterministic event, and the acceleration behavior is not calibrated with data from vehicles at intersections with the particular characteristics of the respective intersection considered.

The models described in this article are one part of a comprehensive research project aimed at closing this gap. Incorporated into simulations they will lead to a realistic representation of turning vehicles' speeds. Combined with models for the path of turning vehicles and gap acceptance models they provide a trajectory model that can be used for safety assessments of conflicts involving turning vehicles. Such a combined model has been developed as part of a project related to ex-ante safety assessments of signalized intersections at Nagoya University.

In Japan (left-hand traffic), the most important conflict types (considering frequency and severity) at signalized intersections are conflicts between left-turning vehicles and pedestrians, and conflicts between right-turning vehicles and cross-traffic. These conflicts have been scrutinized by using video observations from several signalized intersections in Nagoya City. A major objective of this analysis was to understand the influence of different factors, like intersection geometry and layout, on vehicle trajectories.

Scope

The trajectory of turning vehicles is one important factor in understanding how conflicts at signalized intersections can be avoided or mitigated. This applies particularly to the impact of different factors (speed, intersection layout etc.) on the variation of these trajectories. This paper focuses on the modeling of the speed of turning vehicles as part of the trajectory, taking the mentioned influencing factors into account. To incorporate all different possible combinations of these factors, extensive surveys have to be conducted. The results presented in this paper are limited to a common range of different approach angles, intersection sizes, and vehicle speeds. Speed profiles of turning vehicles have to cover the whole distance on which vehicles are influenced by the intersection, i.e. they can begin well before the stop line and end when the vehicle has reached the desired speed for the subsequent road section some distance downstream of the crosswalk. For safety evaluations, however, the area in the intersection is of primary interest. It is assumed that the vehicles do not follow other vehicles (no car-following behavior) and the signal is green (no stop-go decision required). Quantitative results for the speed profiles of turning vehicles unimpeded by other vehicles or pedestrians are given for both left- and right-turning vehicles. The empirical data reveals that the proposed methodology can also be used for vehicles decelerating to yield to pedestrians or other vehicles. The derived *ideal speed profiles* are, hence, the basis for more comprehensive models reflecting the trajectory of turning vehicles.

Outline

The model is based on video observations of signalized intersections. From these observations a mathematical model is derived that can be fitted to the collected speed data. To take intersection layout and constraints into account, the model is calibrated to the available data. Quantitative results of this empirical modeling are presented. Finally, the relevance of the developed model for the safety assessment of signalized intersections is expanded upon. The future extensions to comprehensive trajectory models are explained and the sensitivity to influencing factors and constraints are exemplified.

LITERATURE REVIEW

Many studies deal with accident analysis at signalized intersections, taking all different kinds of influencing factors into account (Kludt et al., 2006, provide a good overview). But accident analysis can only offer an insight into revealed behavior. The prediction of conflict occurrence is thus only possible by deduction. Microscopic simulation tools as a means to overcome this shortcoming with respect to safety improvements of intersections at the planning stage have already reached a high level of sophistication. They receive increasing attention for this new field of application.

In 2003, Gettman and Head investigated into surrogate safety measures obtained from microscopic simulation tools. They listed several requirements on the simulations which have to be fulfilled in order to obtain reliable safety measures which are still not fulfilled by simulation tools. Archer (2004) conducted a more detailed analysis of the opportunities and shortcomings of microscopic simulations for safety assessments. The speed of vehicles was identified as one crucial parameter, but not analyzed on a microscopic level. Viti et al. (2008) compared the observed trajectories of vehicles near the stop line with results obtained by microscopic simulations and found conspicuous differences. The major challenge is the “Less-Than-Perfect Driver” (Xin et al., 2008). The turning behavior of vehicles at signalized intersections is one of the areas where so far no realistic model has been proposed.

On the other hand, Intelligent Transportation Systems (ITS) offer increasing opportunities to collect data and provide drivers with online information on dangerous situations. Many projects focus on these opportunities. Banerjee et al. (2004), Chan (2006), Cody, Nowakowski and Bougler (2007) collected microscopic data of turning vehicles to analyze gap acceptance behavior. But even though speed data was gathered and influencing factors on the driver behavior analyzed, no speed profiles for the basic turning process were developed.

Ahn and Kim (2007) approached vehicle acceleration behavior at signalized intersections by using kinematics. Their objective, however, was to improve queuing models. The speed downstream of the stop line was not scrutinized. Reed (2008) collected trajectory data of turning vehicles at signalized intersections and developed a model for the path of turning vehicles, but also the speed was not further analyzed. Also Saccomanno and Cunto (2006) simplified the speed profiles of turning vehicles in their evaluation of safety countermeasures at intersections.

The maybe most extensive project collecting trajectory data of vehicles is the “100-Car Naturalistic Driving Study” (Dingus, Klauer, Neale, Petersen, Lee, Sudweeks 2006). Probe vehicles traveling normally through street networks continuously collect microscopic data, which includes also trajectory data at signalized intersections. The major focus of the project is the analysis of conflict situations (near-crashes, accidents). The data has not (yet) been used to analyze the turning behavior of vehicles in general and in detail.

No literature could be found addressing the microscopic analysis of the speed of turning vehicles at intersections, despite its importance for deriving reliable surrogate safety measures from traffic flow simulations.

OBSERVATIONS FROM SIGNALZED INTERSECTIONS

Overview

In order to develop a reasonable model for speed profiles of turning vehicles, trajectory data was collected at eight signalized intersections in Nagoya, Japan. The position and time of vehicles was manually tracked on video recordings and subsequently evaluated using an image processing program (TrafficAnalyzer; Suzuki, Nakamura 2008). Thus, more than 350 vehicles have been tracked on 18 approaches. An overview on the survey sites is given in Table 1.

Table 1 Overview of survey sites

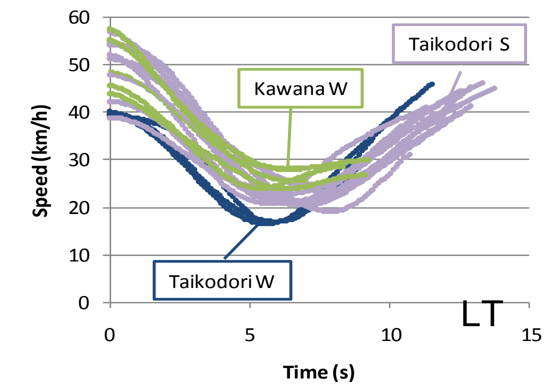
Intersection	Approach	Curb radius LT (m)	Angle LT/RT (deg)	No of tracked vehicles LT/RT (-)
Atsutajingu	N	23	116/64	-/10
Sunadabashi	W	11	90/90	23/12
	N	17	90/90	-/5
Suemoridori 2	N	17	117/63	47/7
	E	10	88/89	72/-
	S	14.5	89/88	-/5
	W	19	63/117	-/10
Kawana	N	17	73/106	-/13
	W	21	106/73	13/-
Sakurayama	S	15	89/91	-/6
Nishiosu	N	15	103/77	-/15
	S	20	103/77	-/2
	W	17	77/103	30/4
Taikodori 3	W	17	94/84	5/17
	N	20	84/94	-/11
	S	17	88/92	14/-
Chikatetsu Horita	S	12	88/88	23/-
	E	14	88/92	11/-
	Range/Total	10-21	65-117	238/117

Data processing

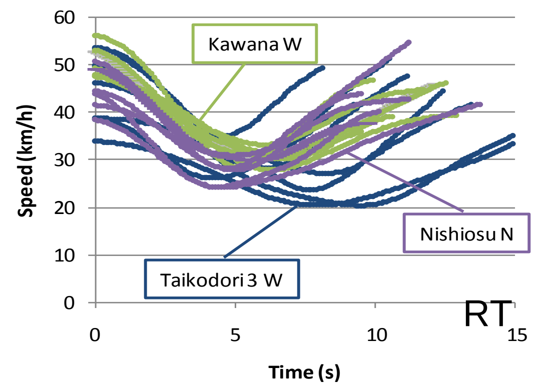
The speed and acceleration of vehicles has been computed from the Kalman smoothed trajectory data (position/time). The trajectories have been divided into different maneuvers: vehicles yielding to pedestrians or other vehicles (distinguished between vehicles which stopped and vehicles which did not stop), and vehicles unimpeded by pedestrians or other vehicles. Here only free flowing vehicles are scrutinized, because their behavior is also the basis for a model describing the reaction of drivers to pedestrians and other vehicles. Only leading vehicles which did not follow another vehicle have been evaluated to avoid a bias due to vehicle following behavior. Some trajectories had to be excluded as outliers due to anomalies in their behavior (e.g. reaction to parked cars, bicycles).

Speed analysis

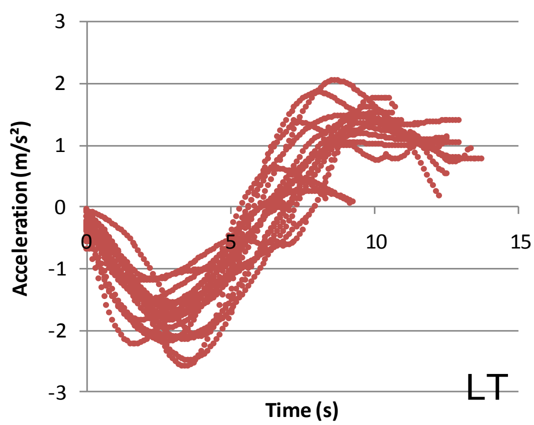
The speed and acceleration profiles of unimpeded turning vehicles follow a regular shape as shown in Figure 1, which shows samples from the collected trajectories (the speeds are distinguished for three approaches by colors, their name indicated).



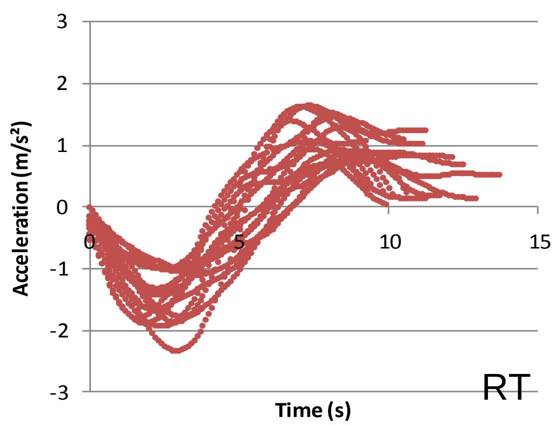
a) Speed profiles of left-turning vehicles at different approaches



b) Speed profiles of right-turning vehicles at different approaches



c) Acceleration profiles of left-turning vehicles



d) Acceleration profiles of right-turning vehicles

Figure 1 Speed and acceleration profiles of left-turning (left) and right-turning (right) vehicles

It can be seen that drivers decelerate smoothly to a minimum speed (somewhere in the curve) before accelerating again to their desired speed. The minimum speed varies as does the time (and location) when it is reached. While the profiles of left- and right turning vehicles is similar in shape, the minimum speed of left-turning vehicles is – not surprisingly, due to the smaller radius (left-hand traffic) – on average lower. Moreover, the deceleration behavior and acceleration behavior of a vehicle do not have to be symmetrical.

The entering speed at the beginning of the maneuver and the exiting speed after the end of the maneuver depend on the desired speed of the driver and the situation on the approach and exit links respectively. These speeds are taken as input values, because they depend on the link conditions and not on the intersection.

In Figure 1 speed profiles observed at the same approach are shown in one color. The difference indicates an influence of the approach on the speed profile. Possible influences are, for instance, the curve radius, the angle between approach and exit, the presence of a raised median and its position. A statistical analysis was conducted to quantify these influences, as will be described further down.

The data shown, furthermore, underlines the random variation of the profiles. Even for identical approach speeds and geometric conditions, two vehicles will rarely follow the same speed profile. This observation can be incorporated into a speed profile model by defining the speed function coefficients and characteristic parameters as random variables.

DERIVATION OF MATHEMATICAL SPEED MODEL

Based on the observations described above a model describing the speed profile of unimpeded (free flowing) turning vehicles was developed.

The speed profile can be divided into two parts, an inflow part and an outflow part, the boundary defined by the moment the vehicle reaches the minimum speed. The acceleration of both parts follows approximately a parabolic shape (cf. Figure 1). If the 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 as shown in Equation. (1) fulfills this requirement. Different coefficients are chosen for the inflow and the outflow.

$$v = c_1 t^3 + c_2 t^2 + c_3 t + c_4 \quad (1)$$

The congruency of the shapes of observed and model speed profile following Equation. (1) is highlighted in Figure 2. The acceleration profile is in this way a polynomial of second degree, the jerk as the first derivative of the acceleration a straight line. The jerk 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.

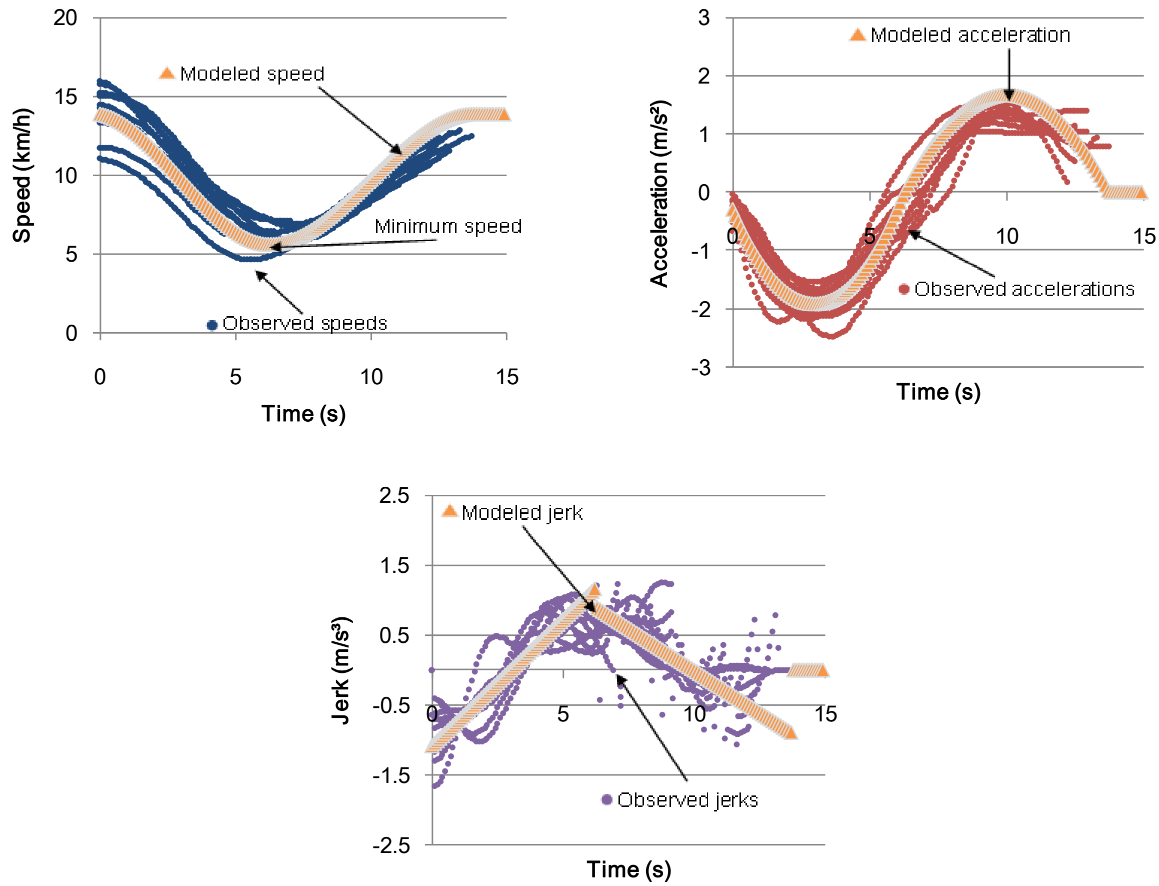


Figure 2 Illustration of model for observed speed profiles, accelerations, and jerk

The principle shape of the speed function and its first and second derivative are illustrated in Figure 3. This general speed profile for turning traffic not influenced by signals, other vehicles, or pedestrians is called *ideal speed profile*. It is divided into an inflow and the outflow part, 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.

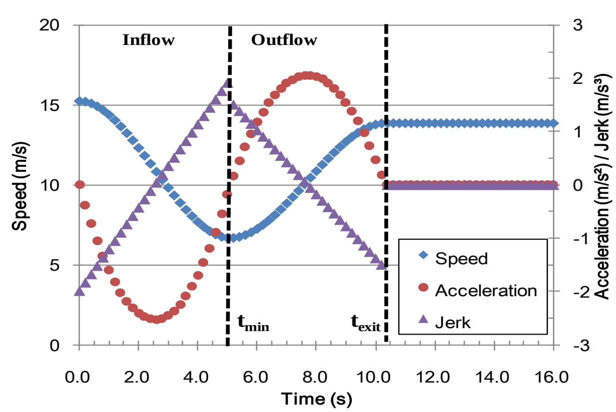


Figure 3 Shape of the speed function with its first and second derivatives (acceleration and jerk)

EMPIRICAL MODELING

Principles

Each speed function is described by four coefficients as shown in Equation. (1). Most of the coefficients are determined by constraints (speed *v* and acceleration *a* at the beginning and the ending of the maneuver, which are taken as model inputs). 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.

Table 2 shows the constraints for the two parts of the ideal speed profile (inflow and outflow) and the parameters/coefficients empirically modeled. "In" denominates the constraints at the beginning of the profile, "out" the constraints at the ending of the profile. The speed function can also be applied to other situations (stopping, accelerating after a stop etc.), which will lead to different constraints. The constraints and coefficients are illustrated in Figure 4.

Table 2 Constraints and modeled parameters for the ideal speed profile of left-turning vehicles

Parameters	Ideal profile (inflow)	Ideal profile (outflow)
Speed *v* (in)	v_{enter}	v_{min}
Speed *v* (out)	(v_{min})	v_{exit}
Acceleration *a* (in)	a_{enter}	0
Acceleration *a* (out)	0	a_{exit}
Time *t* (out)	(t_{min})	$(t_{exit} - t_{min})$
Degree of freedom/constraints	5/3	5/4
Modeled parameter	v_{min}, $c_{1,in}$	$c_{1,out}$

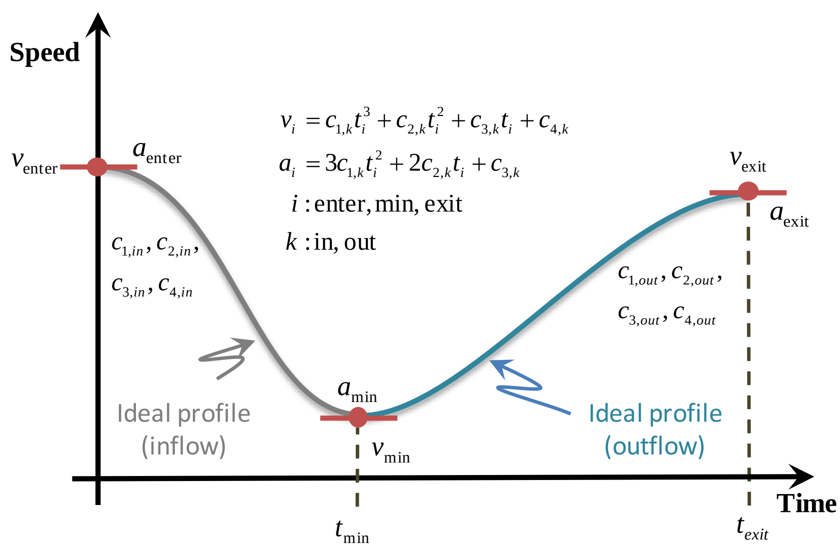


Figure 4 Constraints and coefficients of the speed profile

In addition to v_{min} and c_1, the position of the speed profile relative to the path and, thus, to the intersection is modeled. Because the length of the total turning maneuver varies markedly, but the location where the minimum speed is reached is in the first place related to the curve and therefore limited in variation, the latter position, x_{min}, was chosen to fix the location of the speed profile (Figure 5). The position where the minimum speed is reached is closely related to the path the driver follows. Therefore, the speed profile is related to the path and, thus, indirectly to the intersection geometry on which the path depends.

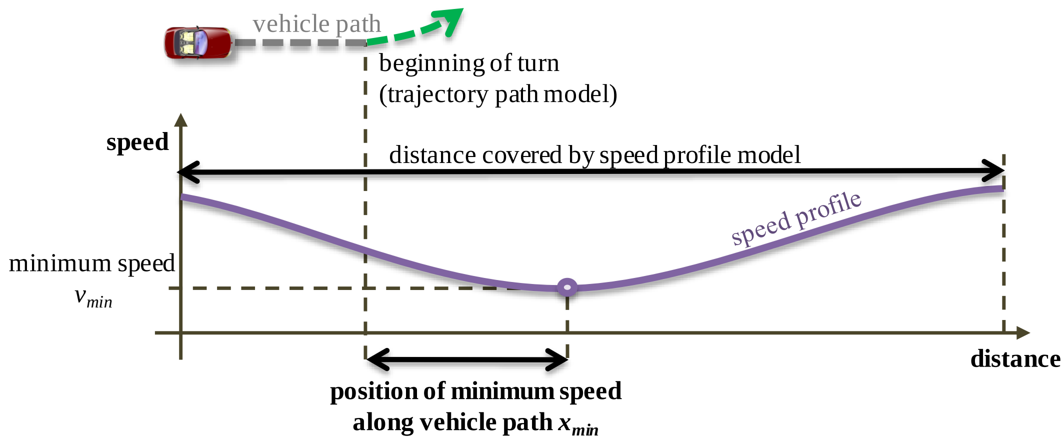


Figure 5 Illustration of the position of the minimum speed, x_{min}, relative to the vehicle path

The effect of different coefficient and parameter values on the speed profile is highlighted in Figure 6. Low absolute values of the coefficients c_1 lead to a profile stretched along the time axis. x_{min} shifts the profile along the time axes.

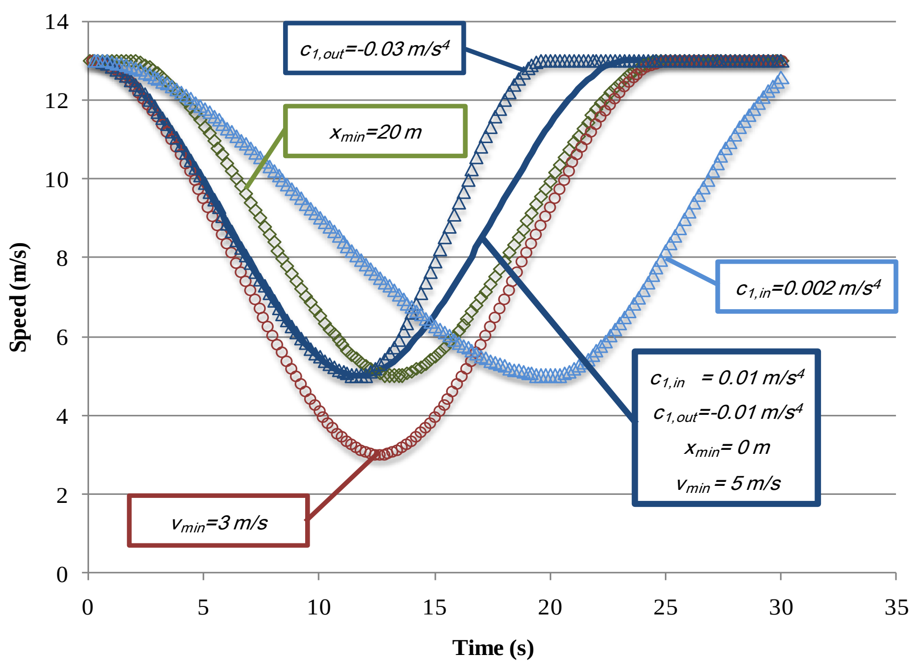


Figure 6 Effect of different speed function coefficients and parameters

The characteristic parameters for the individually chosen random distributions (x representing the modeled parameter) are defined as a linear combination of the influencing factors (X_i) as shown in Equation. (2).

$$x = \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_n X_n \quad (2)$$

Regression analysis was used to estimate the influence of different factors on the characteristics of the speed function separately for left-turning and right-turning vehicles.

Regression analysis

For the regression analysis the trajectory data had first to be classified into the inflow and outflow part of the individual speed profiles and cleaned for outliers by visual inspection. The polynomial speed function was then fitted to each trajectory (separately for inflow and outflow). Thus, the speed function coefficients c_i, minimum speed v_{min}, and position of the minimum speed along the path of the vehicle x_{min} were available together with the respective intersection geometry and vehicle entering and exiting speeds. The overall process is illustrated in Figure 7.

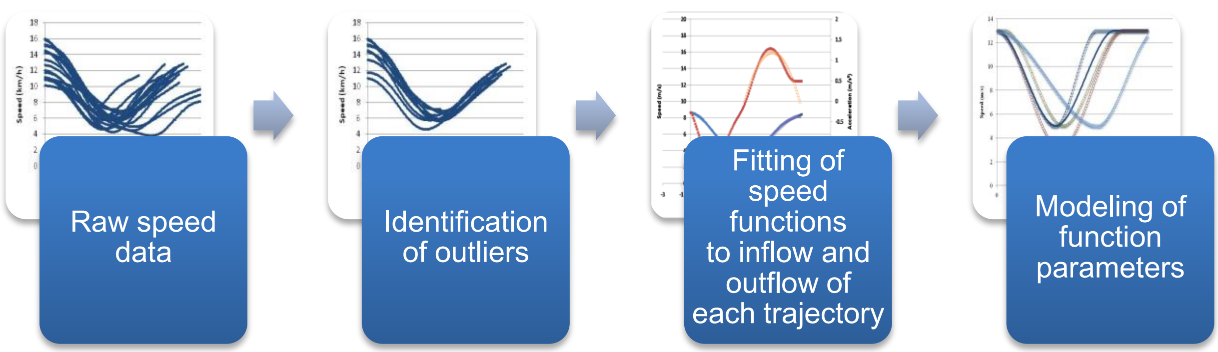


Figure 7 Illustration of overall speed profile modeling process

Least squares fitting was used to derive the coefficients and unknowns of the speed function. Coefficient c_1 and two characteristic points of the speed profile (position along the vehicle path x_{min}, minimum speed v_{min}) incorporate the influences by intersection geometry and driver characteristics. The following factors have been analyzed for correlation with the speed function characteristics (cf. Figure 8):

- approach speed (entry speed) v_{enter} and exiting speed v_{exit}
- approach angle Θ
- curb radius R
- distance of the hard nose to the intersection of the trajectory path tangents ΔHN
- lateral distance of the vehicle in the exit from the curb δ

Approach angle, curb radius and position of the hard nose are given by the intersection geometry. Exiting speed and the lateral distance (exit lane) of the vehicle are determined by the desired trajectory of the vehicle on the road section following the intersection exit, while the approach speed is determined by the vehicle trajectory on the approach.

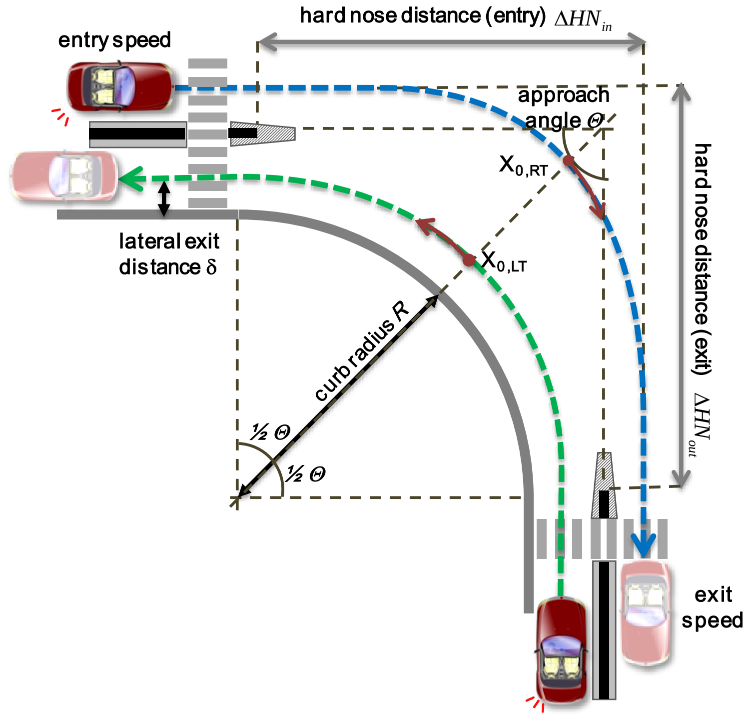


Figure 8 Influencing factors considered in regression analysis

The empirical data reveals that the coefficients c_1 follow a random distribution with positive skew, while v_{min} and x_{min} have a more or less symmetric distribution. Gamma and Normal Distributions have been chosen respectively for the speed profile model.

Results

The models are based on the trajectories of 199 inflow and 187 outflow left-turning vehicles, and on 88 inflow and 68 outflow right-turning vehicles (excluding outliers). Eighteen different intersection approaches with different angles, radii and hard nose positions have been available to analyze the influence of intersection geometry on the speed profiles (cf. Table 1). Based on this sample size the tendency can be shown, even though the exact results concerning the geometry are not particularly reliable and should not be transferred without validation. Based on the available sample size and assuming linear independence, the input parameters used in the models have significant influence on the output at the 90 % confidence interval (z-test).

Table 3 shows the models of the speed function coefficients c_1 for the ideal speed profile. The empirical analysis showed an influence of the entering speed of the vehicle, the approach angle (angle between approach and exit) Θ, the corner radius of the curb R, and the lateral distance of the vehicle from the curb in the exit δ. They follow a distribution with positive skew, hence a Gamma Distribution was chosen for the model.

Table 3 Models of coefficients $c_{1,in}$ and $-c_{1,out}$

Gamma Distribution	Parameters	Left-turning vehicles		Right-turning vehicles	
		$c_{1,in}$ $X \sim \Gamma(\alpha, \beta)$	$-c_{1,out}$ $X \sim \Gamma(\alpha, \beta)$	$c_{1,in}$ $X \sim \Gamma(\alpha, \beta)$	$-c_{1,out}$ $X \sim \Gamma(\alpha, \beta)$
α	Const	2.09	1.41	9.41	5.81
	Entering speed (m/s)	0.256	-	-	-
	Approach angle (deg)	-0.0155	-	-0.0760	-
	Corner radius (m)	-	-		
	Lateral exit distance (m)	-0.168	0.0630		
	Exiting speed (m/s)	-	-		-0.261
β	Const	0.0573	0.0822	-0.055	-0.00260
	Entering speed (m/s)	-0.001729	-	0.00159	-
	Approach angle (deg)			0.000781	0.000250-
	Corner radius (m)	-0.00109	-		
	Lateral exit distance (m)	0.00219	-		
	Exiting speed (m/s)		-0.00396		
Sample Size		199	187	87	66

The results for the minimum speed and the position of the minimum speed are given in Table 4. The position of the minimum speed x_{min} for right-turning vehicles naturally varies more than in case of the left-turning vehicles. The influence of intersection geometry and entering/exiting speed is less significant (only 60-90 % confidence, values in parenthesis). A larger sample size is required to achieve more reliable results.

Table 4 Minimum speed v_{min} and position of minimum speed x_{min} models

Normal Distribution	Parameters	Left-turning vehicles		Right-turning vehicles	
		v_{min} N(μ, σ)	x_{min} N(μ, σ)	v_{min} N(μ, σ)	x_{min} N(μ, σ)
μ	Const	-0.301	1.42	2.650751	(7.346)
	Entering speed (m/s)	0.0908	-	0.1879437	(0.501)
	Corner radius (m)	0.0607	0.586		
	Approach angle (deg)	0.0387	0.0896	0.0289023	(0.0776)
	Lateral exit distance (m)	0.233	0.577		
	Heavy vehicle dummy (HV:1, PC:0)	-0.496	-		
	Distance from IP point to entering hard nose ΔHN_{in} (m)			-	0.288
σ	Const	0.665	0.135	1.404181	
	Entering speed (m/sec)			-	-0.528
	Corner radius (m)	-	0.144		
	Approach angle (degrees)			(-0.00536)	(-0.0350)
	Lateral exit distance (m)	0.0419	0.336		
	Distance from IP point to entering hard nose ΔHN_{in} (m)			--	0.110
Sample Size		199	199	87	87

The developed model for the ideal speed profile of turning vehicles underlines, how the randomness of driver behavior and the influence of different parameters on it can be reflected. Calibrated and validated for the prevailing circumstances these models can be used to predict changes in driver behavior following different intersection layouts. The importance of the models for the safety assessment of signalized intersections is highlighted in the next section.

SPEED PROFILES AND INTERSECTION SAFETY ASSESSMENT

Generalization of speed profiles

The speed profiles discussed above apply to free-flowing vehicles, i.e. vehicles which are not influenced by other vehicles or pedestrians. Comprehensive models for turning maneuvers have to incorporate decision models which reflect the reaction of drivers to pedestrians and other vehicles, which goes beyond the scope of this paper. The decision to yield or pass will determine the choice of a speed profile. In addition to the ideal profiles described in this paper, stopping and yielding profiles can be developed.

Stopping profiles are usually fully determined by constraints, since not only speeds and accelerations at the beginning and ending of the maneuver are known, but commonly also the desired stopping position. Figure 9 shows observed speed profiles of stopping vehicles. Some vehicles reduce the speed only slightly while approaching, but once the driver decides to stop, the profile follows a cubic shape as in an ideal speed profile. Also the acceleration after the stop indicates a cubic shape. Thus, the proposed polynomial can also be applied to stopping profiles.

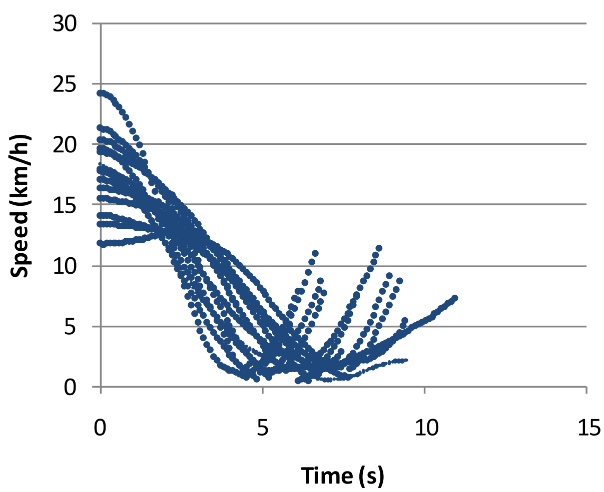


Figure 9 Observed speed profiles of stopping vehicles

Ideal speed profile and stopping profile describe the extreme cases. Many drivers, who react to other traffic participants, will choose a speed ranging between these extremes. Ideal speed profiles and stopping profiles, hence, are required to model turning maneuvers at signalized intersections. The functions describing the ideal speed profile and the methodology to derive the function coefficients and characteristic parameters as described above are, hence, the basis for the comprehensive modeling of vehicle speeds of turning vehicles at signalized intersections.

Integration of speed profile models in simulation tools for safety assessment

As mentioned in the introduction the motivation for the modeling of speed profiles is the development of simulation tools which enable an ex-ante safety assessment of signalized intersections. An ex-ante safety assessment has to be based on conflict analysis. The prediction of conflicts has to reflect the impact of intersection geometry and layout. Conflicts occur randomly. The simulated driver behavior, thus, has to realistically reflect the randomness of the traffic flow.

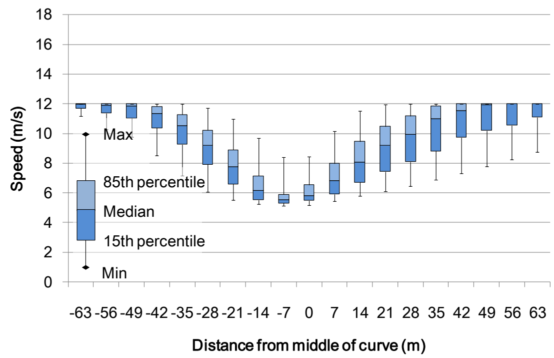
One important part to simulate the traffic flow is the speed of vehicles. Most existing microsimulation tools have already sophisticated models to represent the speed of vehicles on links. The complex decision process of drivers in intersections, however, is commonly simplified by models disregarding many influencing factors, such as the ones shown above to be of importance. This can refer to the intersection geometry, approach and desired exiting speed as well as to the reaction to signals and pedestrians.

The speed profiles described here in combination with models to reflect the driver decision making (i.e. reaction to signals and pedestrians) and models for the generation of vehicle paths (i.e. lateral position of the vehicle with reference to the curb) lead to a realistic simulation of vehicle trajectories inside of intersections (driver reaction and vehicle path models are addressed by separate papers). The model described here is sensitive to intersection geometry and layout. Random profiles are produced which incorporate also extreme behavior, which is crucial for safety assessments.

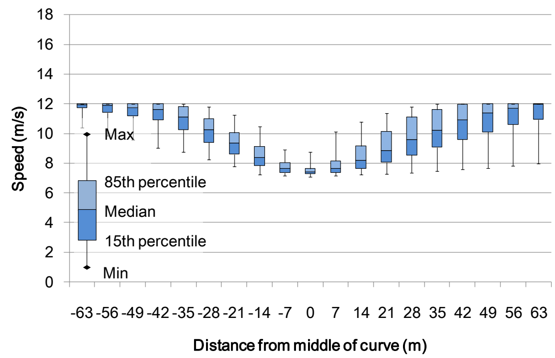
Sensitivity analysis for intersection geometry

To illustrate the impact of different intersection geometries, represented here by the approach angle and the radius of the curb, on the speed profiles, a Monte Carlo Simulation was conducted for the described ideal speed profile models of left-turning vehicles. 100 different random seeds have been used to generate speed profiles. The entering and exiting speed was set to 12 m/s and 15 m/s respectively. The approach angle Θ was set to 70° and 120° respectively. The lateral exit distance δ was fixed to 3 m, the curb radius R to 15 m.

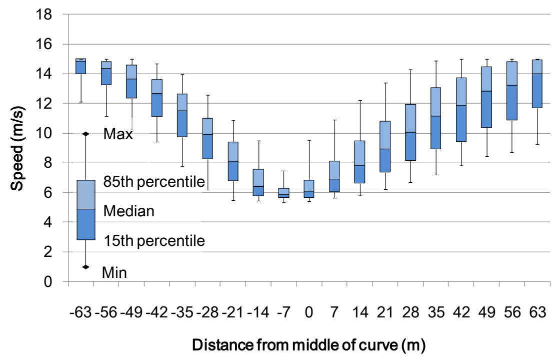
Figure 10 shows box-and-whisker plots of the generated speeds. The data was binned to seven meter distance classes. The boxes represent the 15th and 85th percentile of the speeds in the distance class together with the median. The origin of the distance represents the middle of the curve X_0 (cf. Figure 8).



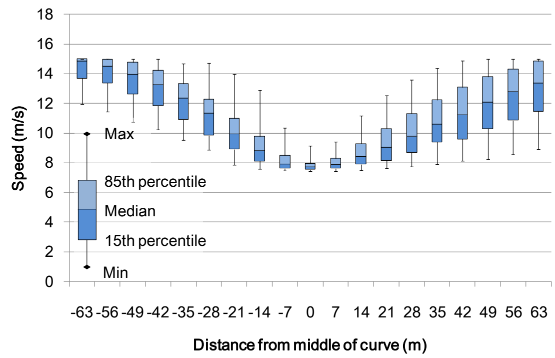
a) Θ = 70° and v_{enter} = 12 m/s



b) Θ = 120° and v_{enter} = 12 m/s



c) Θ = 70° and v_{enter} = 15 m/s



d) Θ = 120° and v_{enter} = 15 m/s

Figure 10 Box plots of modeled speed profiles (left-turn)

The generated data shows the reasonability of the models by reflecting that

- the minimum speed is lower for smaller approach angles and
- the speed variation increases with higher entering/exiting speeds.

The figures also represent the random variation of the speed profiles, which is particularly high near a distance where the conflict points with pedestrians and other vehicles can be expected (10-20 m behind the middle of the curve). Because the entering and exiting speeds will follow a random distribution in itself, this variation is underestimated in the provided data, because the entering and exiting speeds are taken as constant.

In combination with yielding behavior models and pedestrian behavior models similar statistics for the speeds at crucial points in the intersection (e.g. crosswalk) can be produced for all vehicles, including free-flowing and yielding vehicles. With the speeds and time gaps between conflicting traffic participants the important information for the computation of safety indices is available. This information and, hence, the safety indices, will be sensitive to intersection geometry and the speed of vehicles on approach and exit lanes.

CONCLUSIONS AND OUTLOOK

So far safety improvements of signalized intersections are based on experience and ex-post evaluations. The effect of changes in intersection layout or signal timing on the safety cannot be reliably predicted. Microscopic simulations could provide a means to assess the safety ex-ante for different layouts and situations using the conflict technique. This, however, poses high requirements on the driver behavior models used in simulations. One important driver behavior model relates to the turning behavior. Such a model has to consist of sub-models describing the interaction of the driver with signals and other traffic participants, the path of the vehicle, and the speed of the vehicle during the turn.

This paper proposes a model that provides speed profiles of free flowing right- and left-turning vehicles. The generated speed profiles are sensitive to the intersection layout, namely the approach angle, the curb radius, and the position of the hard nose. The profiles follow a random distribution, which is also influenced by the approach and exit speed of the vehicle and its lateral position in the exit.

The developed model was calibrated for big intersections in Nagoya, Japan. It realistically reflects the observed driver behavior. It is a first step towards comprehensive models also taking account of the reaction of the drivers to signals and other traffic participants. For the transferability and application for safety assessments, extensive data has to be collected to calibrate and validate the model for the prevailing situations.

The proposed model was developed as part of an extensive project dealing with the safety assessment of signalized intersections. Further models, for instance, for the paths of vehicles, the speed of pedestrians on the crosswalk, and the start-up and stop-go behavior of vehicles have been developed. The integration in a simulation tool shows the potential of following this approach.

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