BICYCLES IN URBAN AREAS: REVIEW OF EXISTING METHODS FOR MODELING BEHAVIOR

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ABSTRACT

Microscopic traffic simulation tools are often used to evaluate proposed traffic engineering measures and intelligent transportation systems (ITS) before they are implemented. The accuracy and reliability of these evaluations depends heavily upon the realistic modeling of road user behavior within the simulation software. Traditional traffic models focus on the depiction of personal motor vehicles. However, as the number of bicyclists in urban areas continues to increase, the need to realistically model the movement and interactions of bicyclists is rapidly gaining importance in the accurate modeling of mixed urban traffic. In response to this need, a number of approaches to modeling bicyclists' movement and interactions have been developed recently.

Selected modeling approaches that depict the state of the art in bicycle modeling are summarized. The overall modeling of bicycles is divided into that of uninfluenced operational and tactical behavior and influenced operational and tactical behavior. The ability to model bicyclist behavior on each of these levels is evaluated based on the results of an extensive literature review and input from an expert workshop that included industry professionals and academics with extensive experience in traffic modeling.

The results of the assessment indicate that although the approaches used to model uninfluenced and influenced behavior on the operational level vary in their level of detail and ability to correctly reproduce reality, it is possible to model the majority of behavior at this level. There is, however, a need to validate and calibrate these models using empirical data collected from a variety of locations and traffic situations. The state of the art in modeling the tactical behavior of bicyclists is, however, less developed. The uninfluenced and influenced tactical behavior of bicyclists, which has received relatively little attention, is important to model accurately as bicycle behavior is less constrained by road markings and traffic regulations.

INTRODUCTION

Urban planners and governments today are faced with the dilemma of providing high quality mobility services to a growing population, while at the same time minimizing energy consumption, reducing harmful environmental impacts and cultivating a lively and safe urban environment. As a means of meeting these challenges, the bicycle has resurfaced as a valuable transportation mode. Policy revisions and infrastructure amendments aimed at increasing bicycle use have led to a significant increase in the bicycle modal share in many urban areas. As a result, the traffic composition is becoming increasingly heterogeneous, with bicycles, motor vehicles, pedestrians and other road user groups sharing the road space. Planning for the needs of many road user groups with widely varying physical and dynamic characteristics and protecting vulnerable road users, including bicyclists and pedestrians, have become key challenges in urban transportation.

Traffic simulations are a common tool used in assessing proposed transportation measures before these measures are implemented. However, the accuracy and reliability of these assessments depends on the realistic modeling of the movements and interactions of different types of road users. There are a number of characteristics of bicyclists and bicycle traffic that differ considerably from those of car drivers and motor vehicle streams. Due to their very different physical and dynamic characteristics, bicyclists and motor vehicles behave very differently while traveling in urban space. First, the dynamic characteristics of bicyclists, including their speed, acceleration and deceleration profiles differ considerably from those of motor vehicles due to the natural physical limits of bicyclists. Additionally, bicyclists tend to minimize changes in speed and the number of stops in order to reduce the required physical exertion. In contrast from motor vehicle drivers, evidence from empirical studies indicates that bicyclists crossing an intersecting traffic stream prefer to adapt their trajectory (either their speed, lateral position or a combination of both) rather than come to a complete stop and wait (*1*, *2*). Second, physical characteristics, including size and flexibility, differentiate bicyclists from motor vehicles. Because bicycles are much narrower, they are able to utilize lateral space within a traffic lane or bicycle lane to a greater degree than motor vehicles. This lateral flexibility greatly reduces the influence of leading vehicles on the movement of bicyclists. Empirical data indicates that situations where the movement of a bicyclist is limited by the speed and behavior of leading road users over a longer time period occur very seldom (*3*, *4*). Not only do bicyclists have a greater degree of lateral flexibility within a lane, they can also switch easily between different types of available infrastructure (e.g. roadway, bicycle lane or sidewalk). This can lead to bicyclists riding in discordance with the traffic laws (e.g. against the traffic flow, on sidewalks, in pedestrian zones, etc.). Research indicates that in Germany 8-20% of bicyclists ride in the wrong direction, depending on the infrastructure, and 2-15% rides on the sidewalk (*5*, *6*). Alrutz et al. (*5*) found that many bicyclists do not stop at red lights, especially at intersections where a major road crosses a minor road. In Australia, it was found that 6.9% of commuting cyclists run red lights (*7*). The actual portion of bicyclists that break traffic rules likely depends strongly on the bicycle and driving infrastructure and the mobility culture. These differences must be considered and reflected in the modeling of mixed traffic in order to realistically depict these streams in traffic simulations.

The goal of the research project UR:BAN (Urban Space: User oriented assistance systems and network management), a transportation research project funded by the German Federal Ministry of Economics and Technology, is to develop advanced driver assistance systems (ADAS) and intelligent transport systems (ITS) to increase traffic safety and efficiency and to reduce harmful environmental impacts. Within the UR:BAN subproject Human Factors in Traffic, several methods are used to evaluate the impacts of the developed ITS and ADAS solutions, including observations at real test sites, driver simulation studies and microscopic simulation techniques. However, currently available microscopic simulation tools are limited in their capacity to model realistic bicycle trajectories, especially anticipatory and tactical behavior as well as interactions between bicycle and motor vehicle traffic. For this reason, new or extended models will be developed within UR:BAN in order to realistically depict the movement and interactions of bicyclists. These improved tools will make it possible to better assess future bicycle traffic and assistance systems using microscopic simulation techniques.

This paper provides a summary of the first steps that have been taken in the research project. A literature review is carried out in order to identify the unique characteristics of bicycle traffic at intersections and on road segments in urban areas. The existing approaches for modeling bicyclists and their interactions with motor vehicles are thoroughly reviewed and are described in the following section. The models have been organized into four categories, Longitudinally Continuous Models, Cellular Automata, Social Force Models and Logic Models. In the chapter Assessment of Modeling Methods, the ability to realistically model bicycle traffic on four levels, uninfluenced operational, uninfluenced tactical, influenced operational and influenced tactical is assessed. In addition, the results of an expert workshop, including product managers, developers and users of current state of the art microscopic simulation environments, such as VISSIM or SUMO, are included in the assessment section.

Finally, shortcomings in the existing methods for modeling bicycle behavior are summarized and recommendations for future model development are presented in the conclusion.

METHODS OF MODELING BICYCLE MOVEMENT

The majority of currently available and widely used microscopic traffic simulation tools (e.g. Aimsun, SUMO, DRACULA, see (*8*) for detailed description of the state of the art simulation tools) focus on the movement and interaction of motorized vehicles (the main exception being VISSIM). If it is possible to include bicycles in the simulation, they are modeled using the same behavior models used to depict motor vehicle traffic. The parameters are typically adjusted to reflect the lower travelling speed of bicycles. However, several unique characteristics of bicyclist's behavior make the adoption of these traditional vehicle behavior models difficult and, at times, unrealistic. Nevertheless, a number of models have been independently developed to more accurately model bicycle traffic. A selection of these models is summarized in this chapter. This is by no means an exhaustive list of all existing models, but is meant to introduce the main concepts used currently in modeling bicycle behavior.

Longitudinally Continuous Models

The majority of traffic simulation tools utilize two models to independently model the longitudinal and lateral motion of road users (VISSIM, Aimsun, SUMO, etc.). The longitudinal motion models are space continuous and time discrete and typically utilize one of the three types of car following models; Gazis-Herman-Rothery models, safety distance models, and psycho-physical models. All of which use the speed and position of a leading vehicle to determine the behavior of the following vehicle. If there are no other vehicles, or leading vehicles are far enough ahead of the vehicle not to influence the behavior, vehicles strive to maintain a predefined speed. The lateral movement of motor vehicles, and often bicycles, is modeled using a discrete lane choice model, where the position and speed of other road users and the desired route of the individual vehicle are taken into account in the lane choosing process. Lateral movement within a lane is not possible in most discrete choice lane selection models. If mixed traffic streams are simulated using such models, single bicyclists quickly form a moving bottleneck on the road, which is very rarely the case in reality, as faster cars overtake bicycles at the earliest opportunity.

A number of extensions to longitudinal continuous and laterally discrete models have been proposed with the aim of more realistically modeling bicycle traffic. One possibility is to divide the lane into a number of smaller strips and use a discrete model to select the strip within the lane (*9*, *10*). This solution makes it possible for vehicles and bicycles to optimally select their lateral position as well as interact and pass one another within one lane. In addition, because a discrete choice model rather than a continuous lateral model is implemented, the required computing power is still relatively low.

Falkenberg et al. (*3*) proposed a model with a continuous lateral axis. Bicyclists select their lateral position within the lane with the aim of maximizing the minimum Time to Collision (TTC) to other bicycles, pedestrians and motor vehicles. TTC is defined as the time remaining until two road users collide, given they stay on the same path with the same speed. The working principle of the model is shown in Figure 1. The arrows represent the calculated TTC between other road users in the near vicinity. If no other road users are travelling in the near vicinity, bicyclists select their lateral position based on a predefined preference (normally to the right hand side). The longitudinal movement is modeled using one of two Wiedemann psycho-physical models (74 or 99). The authors assume that because bicyclists are also human beings, the same psychological factors (desired speed and following distance) and physical factors (perception threshold and imperfect vehicle control) can be used to determine their following behavior. This assumption was not tested by the authors, but subsequent use of this model in VISSIM (*11*, *12*) has shown that it is quite capable of realistically depicting bicycle traffic in most situations. Carrignon (*11*) noted however that the bicyclists in VISSIM do not interact realistically with the edges of the infrastructure (usually a curb or lane marking) in all situations. Additionally, bicyclists are depicted using a diamond shape instead of the typical rectangle shape used for motor vehicles. This allows for more realistic queuing at stop points in VISSIM.

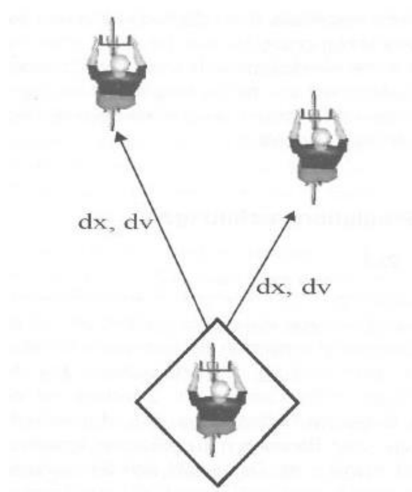

FIGURE 1 Continuous lateral movement model by Falkenberg et al. (*3*).

Cellular Automata Models

Cellular automata (CA) are time and space discrete models. In the original model by Nagel and Schreckenberg (*13*), the two dimensional space is divided into a grid of identically sized cells, each 7.5m long, or roughly the length of one car. Vehicles within the model follow predefined routes through the cell raster using four driving regimes, acceleration, deceleration, randomization and update/move. Cells do not overlap each other and it is not possible for more than one road user to occupy a cell during one time step. For this reason, the original CA from Nagel and Schreckenberg provided a simple and fast method for modeling heterogeneous traffic flows that follow lane discipline. However, the possibilities for modeling mixed traffic streams and the interaction between different modes of transportation are limited. A number of extensions of the original CA have been suggested to make it possible to include bicycle traffic.

One option for including many types of road users in a CA is to create a raster of cells that are sized in accordance with the dimensions of the smallest road user (width and length) and allow road users to occupy more than one cell per time step. This method was used by Yao et al. (*14*) to model situations in China where more than one lane of bicycle traffic runs along a street with one or more lanes of car traffic. Each cell in the model represents 1m x 1m in reality. A bicycle occupies 3x1 cells and a car occupies 5x3 cells. Interactions between bicycles and car are classified into two types: friction and blockage. The driving resistance for car drivers is then determined based on the presence of bicycles in the next lane and by bicycles that leave the bicycle lane and travel into the car lanes. This model has not yet been empirically validated or calibrated.

Mallikarjuna and Ramachandra Rao (*15*) used a similar approach to model mixed traffic streams in India. In this model, the cell lengths are based on the acceleration and deceleration properties of road users and the cell widths are based on the width and observed lateral spacing maintained between different groups of road users. The lateral position of the road users is updated in a first step. In order to consider the different lateral behavior of the road user types, a two lane road is divided into five sub-lanes and five types of lateral movements are defined. The longitudinal position is subsequently updated depending on the acceleration and deceleration characteristics of the road user type and the available space to move forward.

Vasic and Ruskin (*16*, *17*, *18*) developed a CA to depict car traffic and single file bicycle traffic. In this model, a cell raster with appropriately sized cells is created for each type of road user (in this case bicycles and car drivers). When then pathway of more than one stream of road users intersects or overlaps, the cells in this CA model also overlap. The movement of the vehicles is then determined by the impingement of the leading cells. A cell is impinged if it is occupied or any of the overlapping cells are occupied. The lateral interaction between bicycles and cars travelling in the same direction on the same road right of way is only considered on ‘narrow roads’ where the velocity of the cars is limited based on the longitudinal distance to the next leading bicycle. The advantage of the model proposed by Vasic and Ruskin is that the geometry of the intersection can be directly translated into a fitting raster of cells. Complex interactions are extracted from this relatively complex raster of CA cells. Examples of the spatial constructs used by Vasic and Ruskin are shown in Figure 2. This model has not yet been validated or calibrated with empirical data.

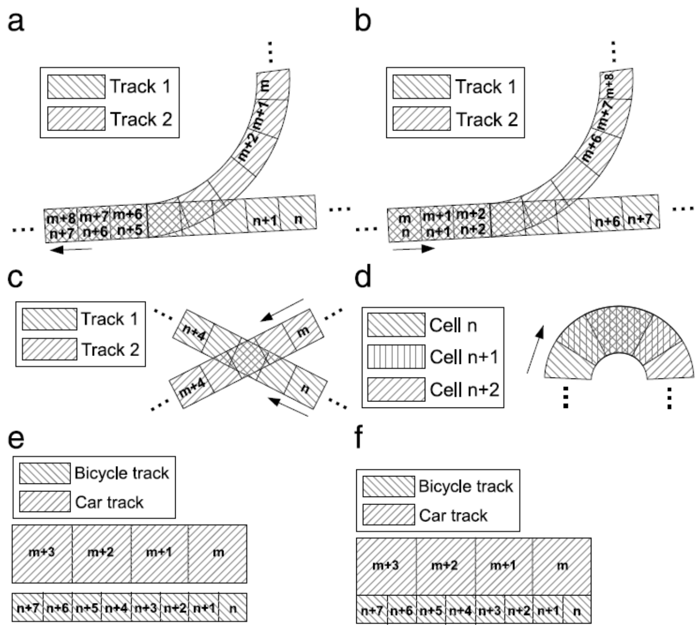

FIGURE 2: Examples of spatial constructs used by Vasic & Ruskin (*16*, *17*, *18*)

Gould and Kramer (*4*) used a CA to attempt to derive the macroscopic properties of bicycles travelling on a one way bicycle lane. The lane was divided into two hypothetical lanes and bicyclists were divided into two groups, slow and fast riders. The model was operated using the extended rules proposed by Rickert et al. (*19*) and was validated and calibrated using empirical data. The results from the simulation provided the following density (bicycles/ft^2) – flow (bicycles/h/ft) relationship. However, no observations were made in reality where the density of bicycles reached or passed a critical level and began to negatively affect the bicycle flow (bicycles/h).

A final option is to allow more than one road user to occupy a cell in one time step (*20*, *21*). This provides a rather macroscopic approach to estimating the capacity of bicycle infrastructure and will not be discussed further.

Social Force Models

A generalized social force model was first proposed by Helbing and Molnar (*22*) in order to model pedestrian dynamics. The basic operating principle of this model is based on the concept that pedestrians move in reaction to the sum of a number of attractive and repulsive forces, namely:

- attraction toward the destination
- repulsion from obstacles
- repulsion from other pedestrians (or other road users)

The movement within social force models is not bound to the longitudinal and lateral axis, but instead modeled road users move freely on a two dimensional plane. However, unlike pedestrians, bicyclists move primarily along the longitudinal axis of the given roadway. A number of models of bicycle models based on an adapted form of the original social force model have been developed and are summarized.

Li, Shi and Chen (*23*) developed a social force model that considers homogeneous automobile and bicycle streams as well as mixed bicycle-automobile traffic streams. The forces acting on bicyclists are a forward driving force that relates the current speed with the desired speed, repulsive forces from other bicyclists and a repulsive force from the edges of the infrastructure that keeps bicycles within the bicycle lane. Bicyclists exit the bicycle lane and ride with the motorized traffic if the density of bicyclists within the bicycle lane is large enough that the repulsive forces from the other bicyclists overtakes the repulsive force from the lane edge. The repulsive force enacted on bicyclists by the motor vehicles in the model is considerably larger than the force enacted by the bicyclists. This is intended to reflect the fact that cars have a greater influence within the road space than bicyclists. This model was not validated or calibrated using empirical data.

Liang, Mao & Xu (*24*) developed a social force model that utilizes two regimes, free flow traffic and congested traffic, to model bicycle traffic. The model used in free flow traffic considers two of the same forces described by Li, Shi and Chen (*23*), a driving force and a repulsive force from other road users (depicted as $\vec{F}^{drv}$ and

$\vec{F}^{ca}$ respectively in Figure 3). Bicyclists are depicted within the model as ellipses. If two bicycles come near enough to one another that their ellipses overlap, a physical model takes over that prevents a collision from occurring. The two forces acting in this case are the contact force $\vec{F}^{cont}$, which counteracts compression of the ellipse and the sliding friction force $\vec{F}^{frc}$, which restricts relative tangential motion, as shown in Figure 4.

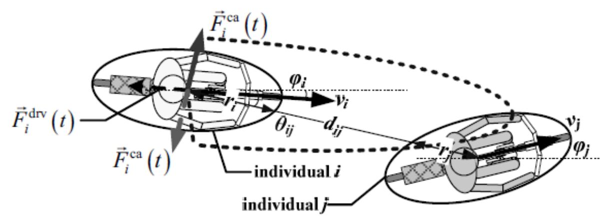

FIGURE 3 Depiction of the social force model by Liang, Mao & Xu (*24*).

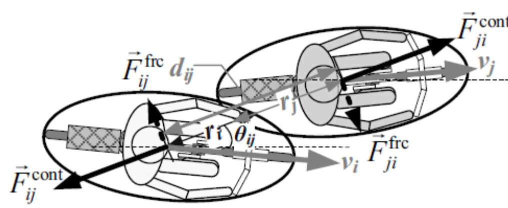

FIGURE 4 Depiction of the physical interaction model by Liang, Mao & Xu (*24*).

Schönauer et al. (*25*) used an adapted social force approach to model intersections with no separated infrastructure for pedestrians, bicyclists and motor vehicles (shared space). All three modes must select their path through the intersection based on the geometry of the infrastructure and the behavior of other road users. This is done using three models, an infrastructure model, an operational model and a tactical model (described in the following section). The infrastructure model builds a force field that uses repulsive forces from the infrastructure edges to push the road users into their intended path. The operational model is again an adapted form of the model proposed by Helbing and Molnar (*22*). In order to consider the reduced degrees of freedom associated with motor vehicles and bicycles, the single track model for car dynamics shown by Kramer (*26*) is used.

Logic Models

Logic model approaches are used to depict the conscious choice behavior, or tactical behavior, of bicyclists, including the selection of infrastructure and the method used to cross intersections. Only a limited number of existing models consider the tactical behavior of bicyclists.

In order to correctly model the movement of road users at uncontrolled intersections with infrastructure that is shared by all road users, Schönauer et al. (*25*) added a tactical force vector to their social force model. The movement of the road users is derived from the sum of the infrastructure guiding force, the adapted social force model and the tactical force model. The tactical force model is based on the Stackelberg game concept (*27*), which is a non-symmetric hierarchical game model with follower and leader players. Potential conflicts between road users are identified based on the planned trajectories of the uninfluenced road users. Various possibilities for avoiding the conflict are considered by both road users. An example of the identification of different strategies, including acceleration, deceleration and dodging left and right is shown in Figure 6.

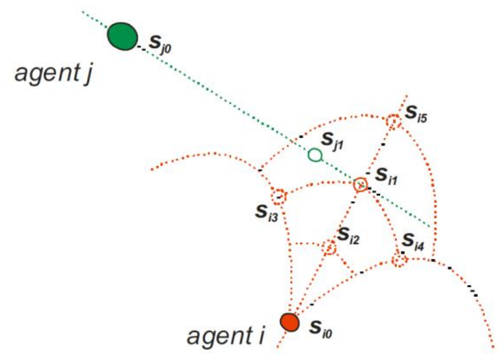

FIGURE 5 Identification of possible options for avoiding a conflict by Schönauer et al. (*25*).

The range of options is created by first determining the strategy of the leading road user and then the reactive strategy of the following road users. The total utility of the strategy is the sum of the partial payoffs for both road users. The validity of the tactical force model has not yet been tested using empirical data.

Huang and Wu (*28*) proposed a model that makes use of fuzzy logic rules to determine the path choosing behavior of bicyclists and uncontrolled intersections. The model consists of three sub-models:

- A situation detection model that detects the speed, direction and position of all other road users within a given area. Conflict points with the detected road users are calculated and fuzzy logic rules are used to estimate the relative danger associated with each.
- A path sketching model that uses the information collected using the situation detection model to determine possible trajectories. The directness, comfort and efficiency are estimated for each of the possible trajectories and fuzzy logic rules are used to evaluate each.
- A reactive path generation model that carries out the path choice and sends information to the situation detection model.

The model was tested using empirical data and the results indicated that the modeled trajectories reflect those observed at the test site.

ASSESSMENT OF MODELING METHODS

The brief description of the models selected in the previous section offers an overview of the state of the art in modeling bicycles. An assessment is carried out to determine the suitability of the currently available models for the assessment of bicycle traffic quality and safety. The categorization used for assessing the state of the art in modeling of bicycle behavior is described below. In each category, the current approaches for modeling bicycle behavior are compared to bicycle movement and interaction in reality. Input from the expert workshop and results from the literature review are used to determine whether identified deficits in each of the categories are necessary to improve in microscopic traffic simulation tools. Whether or not the reviewed models have been validated and calibrated using data from reality was noted during the review and the necessity to implement these steps in the future has been included in the assessment.

Assessment Categorization

The models have been grouped according to the model approach and are assessed separately according to their capacity to model behavior on the tactical and operational level (*29*). An attempt has been made to include relevant models in the assessment. However, no specific number of models was set for each of the categories simply because the number of existing models addressing each category differs.

- The operational level includes the automatic actions carried out by a bicyclist to control the bicycle and ride through the traffic environment, such as speed control, following the road infrastructure and maintaining a safe lateral distance from other object and road users.
- The tactical level includes short term maneuvers that a bicyclist consciously selects to deal with the current traffic situation. Examples of tactical behavior include the avoidance of collisions with other road users and objects through swerving or decelerating and finding a path through an intersection.
- Modeling approaches that deal with behavior on the strategic level, which include planning the trip and selecting a route, have not been assessed as this is not within the scope of the project UR:BAN.

The behavior of road users is divided into two types of movement; the uninfluenced behavior, which occurs when the movement is not affected by the presence or actions of other road users, and the influenced behavior, which is the reaction to the presence or actions of other road users. The models are assessed regarding their capabilities within each sub-category (e.g. uninfluenced operational behavior or influenced tactical behavior).

Assessment Results: Operational Level

There are a number of possibilities for modeling both the uninfluenced and influenced behavior of bicyclists at the operational level. The uninfluenced operational behavior of bicyclists is currently modeled using the one of the following two approaches:

1. Definition of statistical distributions of desired speeds and sets of desired lateral positioning: In this method, bicycle movement is simplified onto one main axis (longitudinal) and the direction of travel is defined using links. Although this approach reduces the realism of the model, the required computing power is also reduced and the speed of the simulation is increased. According to the experts, extended car following models or CA are sufficient for simulation tasks that do not require highly accurate simulation of bicycle traffic. However, if the goal is to analyze the capacity and level of service of intersections or road sections with many bicyclists or to analyze the safety at critical points, the implementation of a more accurate bicycle model is necessary.
2. Implementation of an attractive force: This force from the destination pulls bicyclists in the direction of the destination at a desired speed. Repulsive forces from the obstacles, other road users and the edges of the infrastructure either increase or decrease the travelled speed. Statistical distributions can also be used to vary the desired travelling speed. The main advantage of this approach is that the infrastructure and situation is directly considered in the model. This, however, increases the number of parameters and required computing power.

The influenced behavior on the operational level is also currently modeled using many approaches. Lateral interactions are modeled using discrete choice methods or by implementing a continuous lateral axis and calculating TTC to other road users. The main disadvantage of both types of models is the heavy emphasis on the speed and position of surrounding road users and the lack of consideration of infrastructure and obstacles on the behavior of the individual bicyclist. Additionally, to model the interactions of two intersecting traffic streams, conflict points are often used. At a conflict point, road users in the minor stream must stop at a predefined point on their travel path and wait until a suitably large gap between vehicles presents itself. The bicycle specific characteristic of adapting the speed, lateral position or a combination of both is very difficult, or impossible, to depict in current simulation tools based on car following models. The use of social force models makes it possible to consider interactions with many different road users in both the longitudinal and lateral direction simultaneously. The modeling of interaction on the operative level in CA models is coarser, but requires much less computing power.

According to input from the expert workshop, currently available models can be used to realistically depict bicycle movement on the operational level. However, these models must be calibrated using field data in order to accurately simulate traffic situations. The inclusion of the correct lateral spacing maintained between bicycles and other road users, both while stopped and while riding, is crucial in accurately determining the capacity of intersections and road sections. Similarly, the speed, acceleration and deceleration profiles of bicyclists differ from those of motorized vehicles and must be investigated.

Assessment Results: Tactical Level

An assessment of currently available approaches revealed that far fewer options for modeling such bicycle behavior at the tactical level are currently available. No approaches were identified during the literature review or during the expert workshop that model the uninfluenced tactical behavior. Examples of uninfluenced tactical behavior include the infrastructure selection (bicycle lane, car lane or sidewalk) and the disobeying of traffic laws based on the geometry and signalization of the intersection and presence of obstacles. Although existing simulation tools allow the integration of tactical models – for example the selection probability for a car lane vs. a bicycle lane can be modeled as a function of travel time gain, densities, individual preferences etc. – there is a lack of empirical data that would allow for the identification and calibration of these models.

A small number of models were identified that depict the influenced tactical behavior of bicyclists. The two logic models identified use the position, direction and speed of nearby road users to identify potential conflict points and reassess the bicycle trajectory. The methods used for this reassessment differ between the two models. The model by Li, Shi & Chen (*23*) also considers the tactical selection of infrastructure (bicycle lane and roadway), but only based on the density of bicyclists in the bicycle lane, which is not always realistic in places with less bicycle traffic. Two of the identified models are based upon a social force approach (*30*, *23*). It is not clear which model was used for the movement of the bicyclists in the fuzzy logic model by Huang & Wu (*28*).

It is somewhat difficult to depict tactical behavior using car following models and CA models because the path and travel direction of the road users is predefined. The path selection is then modeled using discrete choice models Therefore, although it is possible to build many situations using these models, it is very difficult to include all the possible tactical decisions of the road users. As the number of paths and the complexity of the path network increases, the required computing capacity also increases. The continuous two-dimensional plane of social force models increases the potential to continuously model of tactical behavior.

The experts in the workshop agreed that there is a lack of understanding as to how bicyclists make tactical choices and subsequently bicycle behavior on this level is included in only a handful of models. However, concerns about the predictability of tactical bicycle behavior including rule breaking behavior were raised by the experts.

CONCLUSION

Although the modeling of bicycle traffic is a relatively undeveloped field, the increase in bicycle traffic in many countries has made the inclusion of bicycle in traffic simulation tools very necessary. Because the behavior of bicyclists is considerably different from that of motorized vehicles, it is not possible to directly adopt models developed for motorized traffic.

This evaluation of current bicycle models and the input from the expert workshop indicates that the approaches used to model uninfluenced and influenced behavior on the operational level vary in their level of detail and ability to correctly reproduce reality. Nevertheless, it is quite possible to model the majority of bicyclist behaviors on this level. It would be very beneficial, however, to validate and calibrate a number of the existing models using empirical data collected in a variety of locations and traffic situations.

The state of the art in modeling the tactical behavior of bicyclists is, however, less developed. The uninfluenced tactical behavior of bicyclists, which has received very little attention, is important to include in models in order to consider how bicyclists behave before their actions are affected by the presence or actions of other road users. Only then is it possible to adapt and change this behavior based on other bicyclists and motor vehicles in the vicinity. As bicyclists are much more flexible than car drivers, the question *why* they behave in the ways they do becomes at least as important as *how* the behave. In order to develop accurate models that depict both the uninfluenced and influenced tactical behavior of bicyclists, empirical data, in the form of both stated and observed preference must be collected in a number of situations.

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