Establishing the validity of cycle path capacity assumptions in the Highway Capacity Manual

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26th October 2016

Abstract

Cycle mode share increase is widely desired, but highway design practitioners lack the numerical tools to deliver infrastructure, instead relying on design standards and intuition, with little literature basis. As a case in point, the US Highway Capacity Manual (which is well-used internationally) has developed levels of service for cycle infrastructure which are, at their core, based on an assumption of non-interaction between multiple cyclists.

This paper uses a modified implementation of the Social Force Model to test the validity of this assumption. Necessary changes such as the consideration of acceleration characteristics and minimum maintainable speed are included. The resulting model produces valid outcomes in keeping with established traffic flow properties reflecting three-phase traffic flow theory and the ability for the stochastic elements in traffic flow to cause flow breakdown.

The developed simulation indicates that there is a fundamental difference in outcome if cyclists are assumed to have a fixed-speed versus one they can change given their surroundings. This difference in outcomes is found to exist within the range of literature design flow capacities for bicycle infrastructure and also yields emergent outcomes which align closely with those known behaviours of highway vehicles which intuitively transfer to cyclists. These findings reinforce the standing need for large-scale empirical

studies to determine the basic numerical and behavioural parameters for cyclists, upon which all design ultimately rests.

1 Introduction

A desire to increase the mode share contribution of cyclists is widely-held (e.g. City of Copenhagen, 2011; Greater London Authority, 2013; New York City Department of Transport, 2008) both as a means to achieving CO_2 emissions reductions (e.g. Walsh, Jakeman, Moles, & O'Regan, 2008) and as a means to reduce the impact of congestion in urban areas (e.g. Buehler, 2012). If such objectives are to be realised then cycling, and supporting planning operational and economic evaluation tools, have an important underpinning role to play in the development of the built environment required to enable it (Willis, Manaugh, & El-Geneidy, 2014).

Modelling and simulation tools for highway motor traffic (e.g. SATURN, Atkins, 2013; Aimsun, Transport Simulation Systems, 2014) and pedestrian spaces (e.g. Legion, Legion Ltd., 2013; Viswalk, PTV, 2013c) are well established in traffic engineering and are widely used. Consequently, when properly calibrated, they have become a standard expectation of the planning process (e.g. City of Portland Oregon, 2009; Transport for London, 2010; Transportation Research Board, 2010) and an important tool for the transport planner. Amongst other benefits, simulation tools allow the ex ante testing and quantification of scheme designs where implementing multiple scheme options is either infeasible or prohibitively expensive.

Yet by contrast, models for the analysis and development of cycle schemes are not similarly established. Empirically-based literature relating to the basic principles of cyclist–cyclist interaction is non-existent. Practitioners usually develop cycle schemes on an essentially qualitative basis (e.g. American Association of State Highway and Transportation Officials, 1999; CROW, 2007; Department for Transport, 2008) and often to arbitrary geometric constraints, with operational value for money measures and the ability to rank comparable schemes by effectiveness, often absent. There is therefore, a standing need for the development of acceptable cycle numerical modelling tools.

A wide review of the academic state-of-the-art of cycle modelling is presented in Twaddle, Schendzielorz, and Fakler (2014). This will not be replicated here, suffice to note that the academic situation is similarly immature as the industrial. Examples referred therein, such as Schönauer, Stubenschrott, Huang, Rudloff, and Fellendorf (2012), also serve to reinforce the view that the academic state of cycle modelling, whilst developing, is not yet ready for wide-scale practical use.

Despite this limited research grounding, the Highway Capacity Manual (Transportation Research Board, 2010) presents a level of service (LoS) measure for cyclists based, at its core, on Botma (1995). Whilst other (primarily subjective) data feed into the LoS measure (Barker, Biehler, Brown, Clark, & Ekern, 2008; Rouphail, Hummer, Milazzo II, & Allen, 1998), the key quantitative measures remain those presented in Botma (1995). LoS are a concept based primarily on the emergent behaviour of traffic at increasing flow levels which results from the interaction of the vehicles with one another. However, as Botma (1995) is explicitly grounded in an assumption of non-interaction of cyclists with one another beyond a simple statistical quantification of meetings/passings (“events”), any qualitative adjustment is potentially going to be based on a core inaccuracy.

This paper takes the Social Force Model (SFM) of a form originally proposed for pedestrians by Helbing and Molnár (1995) and transfers the core principles to cyclists, developing them where necessary. The SFM is an established and validated model which underpins the operation of the major pedestrian microsimulation software packages on the market (i.e. VisWalk, and to a lesser extent Legion) and has been proven through validation and calibration (and subsequent use) to be an effective tool for the design and evaluation of pedestrian schemes. A valid model for cyclists developed in this manner could therefore be similarly calibrated against real cycle behaviour and thus become an appropriate tool for the analysis and development of cycle schemes and interventions.

The application of the model presented here is to the situation considered in Botma (1995). A key part of the (limited) body of quantitative practitioner literature indirectly depends upon this and whilst one could perhaps intuitively consider the issue at high flow levels (only so many bikes can pass each other at once on a given width of roadway), this has not been shown in the literature. Indeed, we show here that even at trivial flow levels, there is a non-zero chance of being prevented from passing/overtaking. The inclusion of an ability of the rider to select speed (as in reality), shows a non-linear relationship with both hysteresis and a step-change toward congestion at high flow levels. This finding is in keeping with observed motor vehicle traffic and theory, and pedestrian observation and theory – both of which can be reasonably assumed to have some transferability to cycling.

Given the industrial reach of the Highway Capacity Manual and that it depends quantitatively on that non-interaction assumption and the criticality of a flow breakdown point in design terms, this paper provides a basis and direction for further research to establish (amongst other quantitative parameters) actual capacity bounds on cycle infrastructure.

2 Background

Simulation modelling in the field of transport is well-established and it is reasonable to assume that principles already validated for other modes are likely (to some degree) to be of use in informing the simulation of bicycle-only (and potentially mixed-modes) flows.

A number of well-studied highway traffic models involving vehicle speed, capacity and service quality are in existence (e.g. Atkins, 2013; PTV, 2013a, 2013b; SIAS, 2000). However, vehicle traffic models generally operate by separating traffic into lanes and thus break the model down into a series of related but separate one-dimensional models. Other workstreams relating to hetereogenous traffic (e.g. Agarwal & Lämmel, 2016; Arasan & Koshy, 2005; Pandey, Ramachandra Rao, & Mohan, 2015), are in the early stages of refinement but are focused upon validation for mixed traffic, and so may have limited applicability to the operation of segregated homogeneous cycle-only infrastructure. Such infrastructure is often considered more appropriate when motor volumes are high, and depends fundamentally upon the direct interactions of cyclists with one another.

Ideally, a robust literature background relating to cyclist behaviour/interaction would be established upon which a model could be constructed. However, no such literature exists. Some literature exists relating to individual cyclists (e.g. vehicle interaction, Parkin & Meyers, 2010; or speed profiles, Parkin & Rotheram, 2010), however literature does not exist where the case of the specific interaction of multiple cyclists with one another is concerned. To take the simple example of bicycle infrastructure capacity (which we will show in this paper depends fundamentally on the interaction of users), compare the literature values for capacity presented in Table 1; note that these vary by multiple orders of magnitude. The interaction of bicycle users with one another is therefore an under-explored research area.

Table 1: Literature capacity measures of unidirectional cycle-only infrastructure

Source	Use	Type	Capacity (bicycles per metre per hour)
(CROW, 2007)	Design Std: Netherlands	Empirical	75-187.5 (width dependent; comfort); 2611–3300 (width dependent; capacity)
(Botma, 1995)	Design Std: USA	Theoretical	650
(Vejdirektoratet, 2012)	Design Std: Denmark	Theoretical	Path up to 2.0m: 1000 Path over 2.0m: 1500
(Navin, 1994)	None	Empirical (with theoretical extrapolation)	4000

In contrast to the highway traffic models noted above, bicycles share some behavioural traits with pedestrians in that they essentially operate in continuous two-dimensional space. In the area of pedestrian modelling, and originally constructed by Helbing and Molnár (1995), the Social Force Model has become an established tool for the modelling of pedestrian movements. The two major commercial pedestrian microsimulation packages in wide use, PTV VisWalk (part of the Vissim package; PTV, 2013c) and Legion (Legion Ltd., 2013) both depend on the principles established by Helbing and Molnár (VisWalk directly, and Legion by way of distillation in Still, 2000). Their validity (when properly calibrated) has led to their wide use in industry and indeed often, an expectation of their use in informing scheme designs (e.g. Transport for London, 2010). Given this, a model based upon the SFM core principles is demonstrated in this paper.

Development of a simple model allows the testing of the basic assumption underpinning Botma (1995) which is that passing/overtaking cyclists do not impede/interact with one another, and that any such event is able to be ignored for all but the most extreme rates of flow. Furthermore, despite that paper presenting its capacity measures as a “proposal” with “preliminary character”, those measures have seen their adoption into the core literature used (internationally) by the practitioner – albeit with some caveats (Rouphail et al., 1998)[1]. Given that the only real quantitative capacity measures in use by practitioners stem from that paper (the other main source being CROW, 2007, which focuses on user comfort not absolute capacity[2]), this is an important assumption to validate. Indeed, Botma makes the point that such testing is required, however no such consideration has occurred in the literature to date.

2.1 The Social Force Model

The model presented here adopts the core principles of the SFM (as proposed originally by Helbing & Molnár, 1995) whilst simultaneously making the necessary modifications to ensure applicability to bicycles. Given there are modifications being applied, a number of different models could have been chosen as a base. The SFM was chosen as it is widely-studied, underpins the VisWalk package of Vissim (PTV, 2013c) which is well-used for pedestrian modelling, and operates in continuous two-dimensional space.

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[1] Rouphail et al. (1998) note that the numbers considered are not absolute capacity measures but the interpretation is the equivalent of considering a highway maximum operational flow to not be the measure of moving vehicle capacity, in contrast to its capacity as a parking lot of the same dimension.

[2] Whilst a theoretical capacity of 3300 bicycles per hour for a cycle path of 1m width (and 4700 bicycles per hour for a 1.8m path) is noted at one point in CROW (2007), the parts of that document focus on the infrastructure, revolve around the comfort values.

The contribution of this paper is the principle of the systematic modelling of cycle flows at all, not simply our methodology.

The SFM operates based on agents navigating a force-field like quantity generated by the presence of the agents in that field (the 'social field', Lewin, 1951). The force represents a metaphorical "motivation to act"; for example, to avoid other agents, to stay with your group, or to avoid fixed objects in the environment. For a full discussion of the basic SFM, the reader is directed to Helbing, Farkas, and Vicsek (2000); Helbing and Johansson (2013); Helbing and Molnár (1995). As a summary, the details of the various aspects of the SFM model, the acceptance or rejection of their relevance, and signposting to the specific sections addressing each, are noted in Table 2.

3 Model Theory

As noted in Section 2, a literature backing for the fundamentals of cyclist interactions simply does not exist. The following Section therefore discusses and presents the theoretical basis upon which modifications to the core SFM have been made.

3.1 Bicycle Force Generation

The spatial arrangement of the force generated by pedestrians is assumed in the SFM to take the form of an ellipse projected in the direction of travel with foci separation equivalent to one walking step length. Pedestrians themselves are considered point objects and make decisions based on an instantaneous perception of the current Social Force field which notionally reflects the probable future arrangement in the spatial distribution. However, changing speed or direction is essentially trivial for the pedestrians; i.e. acceleration is unconstrained. For sufficiently long time steps (in the order of a second or more) this may be essentially true, but if time steps are small (especially if substantially $<$1s) then this starts to become less realistic.

For bicycles, the comparable definition of "sufficiently long" is likely to

Table 2: Comparison, acceptance and rejection of underlying properties of the pedestrian SFM

Principle	Acceptance	Rationale
Agents move through, and due to, a socially generated force field	Accept	Principle is transferable to cyclists if additional kinematic constraints are addressed.
Force field is vectoral	Reject	Vector forces result in potential ‘pushing’ force. Unlikely to be experienced by cyclists in usual operation. See Section 3.1.
Agents are attracted to a waypoint/destination	Partial accept	Agents in our model will continue in their direction of travel until perturbed otherwise. This does not necessitate a destination, though is not incompatible with one.
Agent speeds ‘relax’ to their desired velocity.	Reject	Relaxation implies unbounded acceleration/deceleration. The time frame for speed changes is non-trivial for cyclists. Acceleration is applied based on standard kinematics. See Section 3.4.
Social force spatial profiles are ‘near-future’ distributions of possible location.	Reject	Cyclist speeds and thus time considerations are longer. If accepted then spatial force distributions would be too diffuse to be useful. Future locations are therefore computed by the agents. See Sections 3.1 and 3.4.
Agents are compressible	Reject	Cyclists in contact would likely have crashed. Proximity of cyclists therefore exhibits a step-change. See Section 3.1.
Agents can be attracted to one another (e.g. family/friend groups)	Accept	Equally valid for cyclists as for pedestrians.
Agent perception is variable with angle of view	Partial accept	Concept in original SFM is variable with angle but always non-zero. Rearward visibility for cyclists is much more difficult. See Section 3.3.
Agent speeds vary continuously down to zero	Reject	Below a certain speed, maintaining balance on a bicycle is more difficult, imposing a de facto lower cap on speed with a step down to zero.
Agent speeds are bound at a maximum	Accept	Given the lack of pushing forces noted above, this is accepted and is equal to the cyclist’s desired speed. See Section 3.4.

be longer than that for pedestrians (given higher speeds) and thus longer than is reasonable for the purposes of modelling the interactions. This time frame is limited (in the absolute) by the ability of the rider to deliver power but, given this time length is proportionally long compared to the time frame of interactions, the constraint of the rate of speed change (i.e. acceleration) must be considered for bicycles.

Furthermore, given the higher speeds of cyclists (relative to pedestrians), it is necessary to separate the future situation from instantaneous perception as cyclists need to realistically consider a greater time into the future than is the case for pedestrians. Consequently in this model, bicycles do not consider their exposure to forces at the point which they currently occupy, but consider the forces at a range of projected potential future locations based on extrapolation of where other bicycles will be at the relevant time (given an assumed continuation of other bicycles' current behaviour until that time in the future) and the kinematic constraints of the considering agent's current speed and possible range of turn prior to that future point. Future force returns at those potential locations are discounted with increasing time to account for the uncertainty in future decisions of the other bicycles; essentially producing a net present value for the force on each considered path choice (in essence, a 'net present force'; see Section 3.4). Force returns include whichever repulsive and attractive forces are present in the given simulation, although for simplicity all attractive forces are set equal to zero (i.e. there is no grouping of cyclists or waypointing) in the demonstration that follows in Section 5 onwards. Cyclists navigate the force field, seeking vectors that minimise their overall exposure to repulsive force as calculated in each time step.

Simply modifying the SFM's spatial force projections, which embody the uncertainty about the next few steps of the pedestrian, to fit the above parameters (i.e. projecting through an extended time step) would not produce acceptable outcomes owing to the extensive and diffuse spatial distribution of the projected force that would result given the speed, extended time consideration and potential range of motion of the cyclist.

Bicycle force generation is proposed to be generated with an exponential distribution akin to the SFM but with an additional overlay reflecting the cyclist envelope. Pedestrians in the SFM are treated as point objects (Helbing & Molnár, 1995); by contrast, bicycles cannot compress one another (Helbing, Buzna, Johansson, & Werner, 2005) nor rub against one another (Helbing et al., 2000) and simultaneously maintain the ability to cycle (compared to pedestrians which to some extent, are 'compressible'). Physical contact between cycles is almost certainly, by definition, a crash and is not recoverable in trivial time. The equivalent in a pedestrian model would be pedestrians physically falling over one another. Clearly, such a mode of operation is not appropriate for 'usual' operation and thus is not proposed to be transferred to the bicycle model here. As an alternative, it is proposed to overlay a force equal to the bicycle maximum[3] over the spatial area of the bicycle (i.e. the rectangular area in Figure 1). For simplicity, this is approximated to a rectangle with dimensions equating to a bicycle. Such a dimension incorporates the rider, clearance for steering and potential panniers etc. For the remaining bicycle force, elliptical spatial force profiles are proposed centred on the cyclist (and orientated longitudinally; Figure 1b) reflecting the inappropriateness of a circular approximation for a bicycle/cyclist combination (see Section 4.4).

3.2 Boundary Force Generation

Boundary exponential force distributions (as per the original SFM) result in a model in which the ultimate calibrated balance of forces is sensitive to path width as an exponential distribution has infinite extent. To avoid this, and given that cyclist boundary effects are currently poorly understood, a simple linear function for force is proposed (Section 4.5) which decreases with distance from the boundary and reaches zero at a given distance (i.e. approximating edge-shyness; Department for Transport, 2008). Thus, the balance of the interactions with other bicycles and with the boundaries is broadly decoupled from the path width for the purpose of this model, with the exception of those in close proximity to the path edge where avoidance behaviour is as expected.

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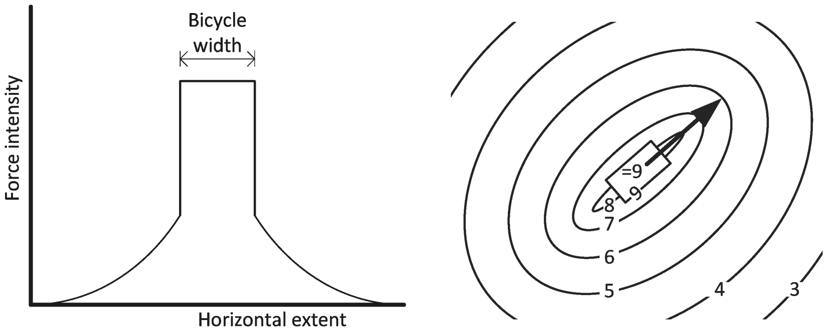
[3] I.e. that which would be calculated at a 0.0m from the location of the bicycle. The exact number is a function of the parameters chosen.

Figure 1: Illustrative force profiles (arbitrary scales/values)



(a) Section through bicycle force profile

(b) Plan view of ‘isopotentials’ (arbitrary values)

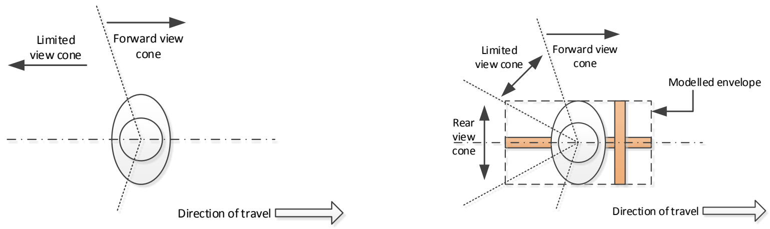
3.3 Force Perception

The SFM considers the potential of a view-cone and Helbing and Molnár (1995) proposed a reduction factor of 0.5 for pedestrians outside of it (i.e. to the rear). However, combined with the directionality of the force, the result is a ‘pushing’ force from a pedestrian approaching from behind. Helbing and Molnár were primarily concerned with crowd crushes wherein such pushing forces are explicitly non-trivial. Future development to the SFM (e.g. Helbing et al., 2005) revised this to a continuous anisotropic λ parameter, however, for the purposes used here, a simple augmented zonal view-cone is sufficient when considering the issue from first-principles.

For bicycles in ‘usual operation’, a simple reduction by half of the perceived effect of other cyclists to the rear is not realistic for two reasons. Firstly, a reduction factor in the order of a half for anywhere outside the view-cone is suggested for pedestrians, but it requires substantially more effort to look directly behind safely whilst cycling than is the case for walking, thus reducing the ability to perceive such a force. Secondly, it is debatable whether a cyclist would feel any non-trivial requirement to cycle substantially faster due to a perceived social pressure of cyclist(s) behind them. The second issue is alleviated through the use of a scalar force field which, given the proposed directional choice algorithm, does not fundamentally change the operation of the model. With regard to the reduction factor, three different perception profiles are proposed (see Figure 2):

- If the perceived bicycle is within the forward view-cone, then the full force effect of that bicycle is perceived. This area requires no effort to view on behalf of the perceiving cyclist.
- If the perceived bicycle is within one of the side view-cones then notionally, this would require the cyclist to turn his or her head to observe them. This requires effort on behalf of the cyclist and may result in them not being observed if the cyclist is otherwise engaged. This equates with the side blind-spots for a motor vehicle driver. As a result, the effect of bicycles present within these view-sectors is reduced.
- If the perceived bicycle is not within the side or front view-cones, then the cyclist would have to turn their head and torso simultaneously to look behind; a difficult task on a bicycle whilst maintaining full control. Consequently, the effect of these bicycles are perceived less than the side view-cones (if at all).

Figure 2: Illustrative view cones



(a) Original Social Force Model

(b) Proposed in this model

Perception of the force field ahead of the cyclist is condensed to a ‘net present force’ on each potential vector choice. The vector with the least repulsive (or most attractive) net present force is selected. This ensures that cyclists react most to obstacles close to them rather than those further away and that the greater certainty of the imminent situation is reflected in the force perception. As each cyclist makes this consideration once per time step, the cyclist can react appropriately to the changing circumstances around them, as they unfold.

3.4 Bicycle Speed Selection

Pedestrian speed in the SFM is only bounded at the maximum; i.e. pedestrians can move at very low speeds. Whilst this may be realistic for pedestrians who can essentially reduce step length and walking cadence continuously to zero, cyclists are limited by a minimum speed below which they cannot maintain balance on the bicycle and (usually) react by lowering one or both feet to the ground.

Acceleration is proposed to be applied to the bicycle using the appropriate kinematic equations of motion (assuming uniform linear acceleration during that time step) with resulting speeds capped at the desired maximum and by the minimum sustainable (which if the speed would fall below, then a ‘foot down’ stopping state is activated). For this model, acceleration is simply assumed to be invariant with speed as there is a lack of any empirically-backed literature to the contrary.

Speed selection therefore takes place realistically rather than being abstracted to a “relaxation parameter” as in the original SFM. Acceleration in the model is modified by the cyclists’ perception of the force field ahead of them on their chosen path. This too replicates real behaviour where speed selection is achieved through the application of braking or by acceleration.

4 Model Implementation

4.1 Model Structure

The model for each cyclist agent follows the structure detailed in Figure 3 which parallels the SFM as formulated in Helbing and Molnár (1995). However in structural terms, it should be noted that the complexities of cycle behaviour over those of pedestrians mean that the proposed model is not entirely built upon mathematical abstraction (as per the SFM); in common with many models, some aspects are algorithmic and/or iterative in nature[4].

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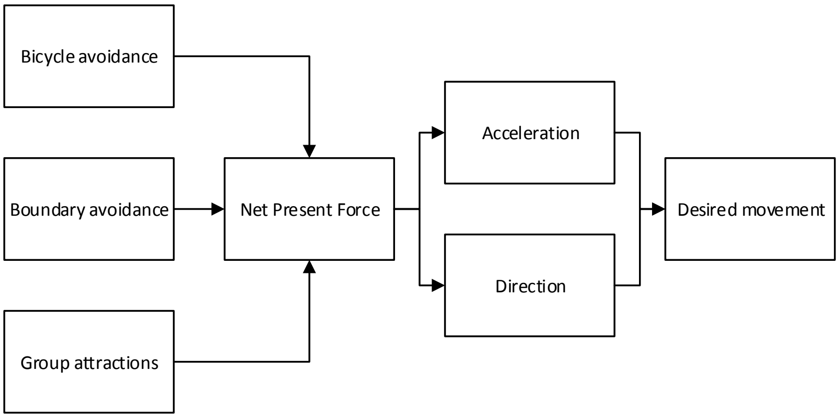
[4] E.g. the rule-based lane selection algorithm in PTV (2009), detailed in Barcelo (2010).

Whilst this may impact upon the elegance, for an ultimate use case in simulation, this does not impact the validity of the proposed model.

Figure 3: Structure of the proposed SFM



At the highest level, the model is designed to be run iteratively, where time is stepped by a fixed amount (t_{step}) between iterations, every cyclist is iterated through once at each time step (according to the process defined in Figure 3), and the location/speed of each cyclist is subsequently updated once per time step (once all other calculations are complete).

4.2 Desired Movement

In the SFM, desired movement is defined numerically as a combined function of the desired speed and direction of movement, and/or a relaxation to this. The resultant behaviour of the pedestrian then being affected by the social force. In this model, the concept of desired movement is emergent from the tendency, in the absence of any social force, for bicycles to travel in the desired direction and at the desired speed. Following perturbation, travel direction returns to the desired and speed returns to desired at a rate bounded by maximum acceleration. Speed and direction of travel are independently changed as follows:

4.2.1 Speed

As with the pedestrian SFM, this cyclist SFM gives the cyclist a desired speed. For the purpose of modelling and in the absence of experimental data, a normally-distributed speed distribution is assumed.

Resultant speed is defined as a function of acceleration and speed in the previous iteration time step; itself calculated from the perception of social force on the chosen route. At each time step, acceleration is applied as constant linear acceleration for the duration of the time step, and using the relevant kinematic equation of linear motion (Equation 1). Consequently, the need for a critical, yet practically abstract, 'relaxation' parameter is avoided.

$$v(t) = \begin{cases} v(t - t_{step}) + (a(t) \times t_{step}) \\ \qquad \text{if } \leq v_{desired}\text{; or} \\ v_{desired} \\ \qquad \text{if } > v_{desired}. \end{cases} \tag{1}$$

where $v(t)$ is the new speed in the current time step, $v(t - t_{step})$ the speed in the previous time step, $a(t)$ the current acceleration and t_{step} the length of the simulation step.

Acceleration is equal to the desired acceleration (a_{max}) which is reduced based on the overall net present repulsive force perceived on the chosen direction of travel ($netPresentForce$) adjusted by calibration with a $crowdingFactor$, which if sufficient, results in deceleration and thus slowing (Equation 2). Such a deceleration is bounded by the maximum deceleration parameter (a_{min}). In the absence of any literature to the contrary, acceleration is considered independently of the speed, though it is accepted that this may not be the case in reality.

$$a(t) = \max\Big(\big(a_{max} - (crowdingFactor \times netPresentForce)\big),\ a_{min}\Big) \tag{2}$$

4.2.2 Direction

Desired direction of movement is defined in the SFM as the direction from the current position to the next waypoint/destination. This model proposes similar in the absence of any surrounding social force.

However, the pedestrian SFM modifies the direction of travel vector (i.e. the velocity) instantaneously according to the ambient social force. Here instead, speed and direction are decoupled and the social force is aggregated into a net present force, which is perceived on each available direction of travel. The direction of travel chosen at each time step is simply the available direction of travel with the most attractive (or least unattractive) social force exposure. In that sense, motion is an agent ‘choice’ based on planning, rather than an immediate reaction to the surroundings.

4.3 Net Present Social Force

The concept of a net present force is key to this implementation of the SFM. The discount to a net present value follows established economics principles and is defined by Equation 3:

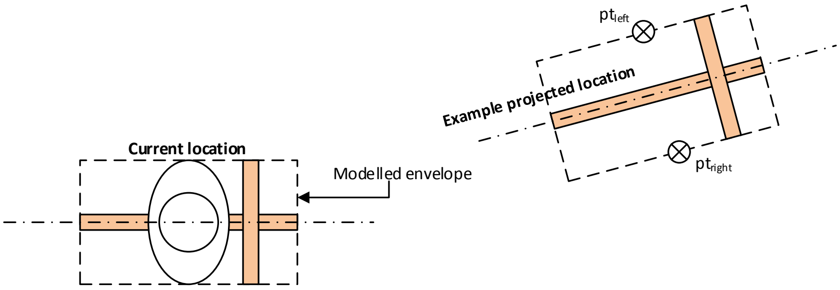
$$netPresentForce := \sum_{u=plan_{step}}^{u=plan_{max}} \exp\left(-\lambda \times \left(\frac{u}{plan_{step}} - 1\right)\right) \times \left(force(pt_{left}) + force(pt_{right})\right) \tag{3}$$

where u is the current planning step ahead being considered, $plan_{step}$ is the minimum planning step duration considered, $plan_{max}$ is the maximum time ahead being considered and λ is the decay constant. Force at the current position is not considered. $force(pt_{left})$ and $force(pt_{right})$ are the returned forces at that planning time step for a point on the left and right extents of the bicycle envelope on the given vector (see Figure 4). This is included so the bicycles do not attempt to force their way through gaps that are too small to pass through, should a single point on that vector happen to fall between two close objects.

The force returned at a given point and time (pt) is the sum of the repulsive force of all other bicycles ($force_{bicycle}$), boundaries ($force_{boundary}$) and any attractive forces from other bicycles ($forceAttraction_{bicycle}$; Equation 4):

$$force(pt) := \sum^{i} force_{bicycle_i} + \sum^{j} force_{boundary_j} + \sum^{i} forceAttraction_{bicycle_i} \tag{4}$$

Figure 4: Indicative example of arrangement of pt_{left} and pt_{right} used in force computation



4.4 Bicycle Repulsive Force Generation

The repulsive force of each bicycle is generated according to Equation 5:

$$force_{bicycle}(pt) := \begin{cases} forceScale_{bicycle} \times \exp\left(\frac{bikeWidth - b}{forceSpread_{bicycles}}\right) \\ \qquad \text{if } pt \text{ is not within the bicycle spatial envelope; or} \\ forceScale_{bicycle} \times \exp\left(\frac{bikeWidth}{forceSpread_{bicycles}}\right) \\ \qquad \text{if } pt \text{ is within the bicycle spatial envelope.} \end{cases} \tag{5}$$

where pt is the point for which force is to be calculated and b is the semi-minor axis length of the elliptical ‘isopotential’ coincident with that point (Figure 1b).

$$b := \frac{\sqrt{(df_1 + df_2)^2 - (df_{inter})^2}}{2} \tag{6}$$

b is calculated as per Equation 6 where df_1 is the distance from the point of interest to the rear focus, df_2 is the distance from the same point to the front focus and df_{inter} is the inter-foci distance.

4.5 Boundary Force Generation

Boundary forces are generated according to a simple linear function (Equation 7):

$$force(pt) := \max\Big(forceScale_{boundary} - \big(forceSpread_{boundary} \times d\big)\,,\,0\Big) \tag{7}$$

where d is the perpendicular distance from the point of interest to the boundary concerned. If repulsive forces are defined to increase in the positive (i.e. ‘more’ force is repulsive), then the maximum value is chosen as shown here. If repulsive forces are defined to increase negative (i.e. ‘more’ force is attractive), the reverse is true. Care must be taken to ensure consistency of signing (i.e. boundaries should always be repulsive), however the choice of signing for either repulsive or attractive force as positive, is the choice of the modeller.

4.6 Bicycle Attractive Force Generation

The attractive force of each bicycle is generated according to Equation 8:

$$forceAttraction_{bicycle}(pt) := \begin{cases} related_i \times forceAttractionScale_{bicycle} \times \exp\left(\frac{bikeWidth - b}{forceAttractionSpread_{bicycles}}\right) \\ \qquad \text{if } pt \text{ is not within the bicycle spatial envelope; or} \\ 0 \\ \qquad \text{if } pt \text{ is within the bicycle spatial envelope.} \end{cases} \tag{8}$$

Attractive forces are defined in a similar manner to the repulsive forces discussed above, however no attractive force is returned for the area within the spatial envelope of the cyclist. As noted above, this is not a desirable area for another cyclist to seek as it would result in a collision, thus no attractive force should be experienced at that point.

Parameters for the spatial distribution of the attractive force ($forceAttractionScale_{bicycle}$ and $forceAttractionSpread_{bicycle}$) are defined similarly to repulsive force, save that if repulsive force is defined positive, then attractive force must be negative, or vice versa.

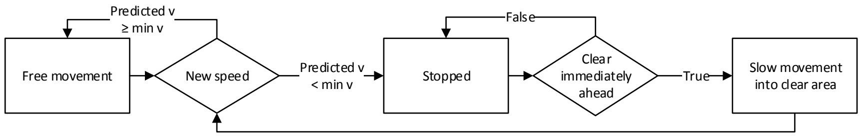
Appropriate calibration ensures groups of ‘related’ cyclists remain apart yet still attempt travel in a proximate group. The existence of an attractive force between given bicycles, depends on them being defined in the same group or not; $related_i$ being between 1.0 and 0.0 depending on if a relationship exists between the bicycle concerned and the other bicycle being considered (i.e. no force is returned if the two cyclists do not have a grouping relationship) and allowing for a tunable strength to that relationship.

4.7 Stopping

The model presented thus far produces outputs (when appropriately calibrated) that appear valid at low densities of flow. However, there is an already identified issue (Section 3.4) with bicycles which is not yet included: namely, that there is a minimum speed that cyclists can maintain before they need to put one or both feet down, and stop.

A final consideration must therefore be overlaid upon the resulting new speed calculated in each time step. In this regard, the cyclist can be considered as a ‘state machine’ illustrated in Figure 5.

Figure 5: Cycle state machine arrangement



A cyclist exhibits movement until such time as the speed of the cyclist falls below the minimum speed threshold. At this time, the cyclist stops (by lowering one or both feet), which given the low speed, can be assumed instantaneous (i.e. stopping occurs within a single time step). Thus far (and in reality), the distance considered ahead is (indirectly) a function of the cyclist’s speed — the cyclist considers a given time ahead, a faster cyclist therefore considers a greater distance. When the cyclist stops, such a consideration is no longer appropriate. Instead, the cyclist considers, “Is the area immediately ahead clear?” If this is the case then the cyclist moves off at a minimum speed for as long as it takes to traverse that distance already considered and known to be clear (in this time, the cyclist is regaining their balance). Once that time has passed, consideration is as the standard behaviour where, if the space ahead is clear, the cyclist will accelerate away; if not, then the cyclist may again slow below the minimum threshold and stop again.

Algorithmically, this represents appropriate cycle behaviour relating to moving off or stop-go queuing and is included here in such a manner as this is an implementation aspect of the model, rather than mathematical. The model retains substantial validity without such a consideration, however as discussed (Section 3.4), the ability of a cyclist to travel at potentially infinitesimal speeds is unrealistic.

5 Simulation Design

5.1 Implementation and Parameters

An agent-based computer simulation was built which implemented the model described. For simplicity, no grouping of cyclists was assumed (i.e. only repulsive forces were present) and unidirectional flow in two-dimensional space was considered on paths of fixed widths (1.0m–10.0m; in steps 0.1m) and parallel sides and a length[5] of 60m. Bicycles arrive stochastically according to Poisson-distributed arrival intervals (based on a set overall rate for the run) and at random lateral positions in the pathway at rates of 100–5000 bicycles per hour (in steps of 100 bicycles per hour). To reduce the effect of stochastic noise, 25 runs per parameter combination were undertaken.

All bicycles are assumed equal in terms of parameters, the exception being their individually desired speed which is drawn from a Normal distribution with the specified parameters (Table 3). Those, and the other literature parameters used in this implementation, are taken from CROW (2007) which ensures that they have some element of empirical backing. Though perhaps intuitively low (e.g. a mean of 4.02ms^{-1}), this source also provide

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[5] Testing of the model indicated that beyond the length used in this paper for this particular scenario (parallel-sided path), output parameters were substantially unchanged, however the runtime of the simulation would rapidly become intractable.

values for standard deviation and acceleration/deceleration, so they can be considered to be at least internally consistent within the given (in this case Dutch) population.

Minimum speed is however taken from Navin (1994) as no such value is included in CROW (2007) and no other literature exists. Model parameters for the intensity of the social forces were chosen using visual observation of the simulation running, using informed approximations (such as the angles of sight utilised) in order to produce outputs commensurate with intuitive and empirical knowledge; e.g. forces were calibrated to allow virtual lanes of approximately 1.0m width to form, in keeping with the dynamic envelope of the cyclist specified in Department for Transport (2008) and elsewhere (though it should be noted the empirical basis for such a value is, in itself, unproven). All parameters used in the preparation of the data presented in this paper are detailed in Table 3.

5.2 Simulation Outcomes

The two parameter variables – path width and bicycle arrival rate – are essentially covariant if expressed in terms of flow density. For the purpose of the following, these are therefore combined into a bicycles per metre width per hour (bpmph) measure. Two sets of the parameter sweeps discussed above (Section 5) were completed: one with all agents set such that they could not vary their speed (i.e. $v(t)$ was fixed to $v_{desired}$ for each agent), and the other as described above. All other parameters remained fixed. The former scenario therefore uses the assumption from Botma (1995), whereas the latter does not. Should the assumption be valid, we would expect to observe a similar output from both sets across a range of input parameters. The result of this comparison is shown in Figure 6.

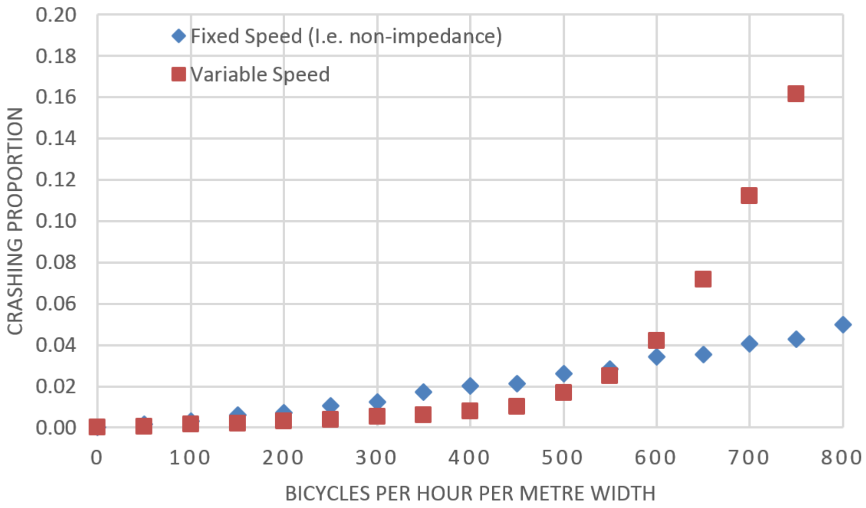
For fixed speed operation, the output indicates a proportion of agents are experiencing a ‘crashing’ state across essentially all arrival rates with proportions steadily increasing. The implication of this being that the interaction of bicycles is potentially non-negligible, even at the low end of flow rates.

For variable speed operation, a fundamentally different outcome is ob-

Table 3: Model Parameters

Parameter	Symbol	Value
Simulation time step	t_{step}	0.1s
Simulation length		300.0s
Bicycle traversal length		75.0m
Boundary force spread (Department for Transport, 2008)	$forceSpread_{boundary}$	500
Boundary force scaling	$forceScale_{boundary}$	10000
Bicycle force spread	$forceSpread_{bicycles}$	75
Bicycle force scaling	$forceScale_{bicycles}$	375
Bicycle attractive force spread	$forceAttractiveSpread_{bicycles}$	75
Bicycle attractive force scaling	$forceAttractiveScale_{bicycles}$	0
Bicycle force ellipse foci separation	df_{inter}	5000mm
Bicycle width		750mm
Bicycle length		1800mm
Bicycle fleet speed mean (CROW, 2007)		4.02ms^{-1}
Bicycle fleet speed standard deviation (CROW, 2007)		0.21ms^{-1}
Bicycle fleet maximum acceleration (CROW, 2007)	a_{max}	$+1.0\text{ms}^{-2}$
Bicycle fleet maximum deceleration (CROW, 2007)	a_{min}	-1.5ms^{-2}
Bicycle minimum speed (Navin, 1994)		0.92ms^{-1}
Bicycle maximum steering angle		40.0°
Bicycle steering step		4.0°
Bicycle forward planning step	$plan_{step}$	0.25s
Bicycle forward max planning time	$plan_{max}$	5.0s
Bicycle forward planning decay constant	λ	1.0
Bicycle angle of sight		±100.0°
Bicycle angle of reduced sight		±160.0°
Crowding reaction factor	$crowdingFactor$	0.4
Side reaction factor		0.1
Rear reaction factor		0.0

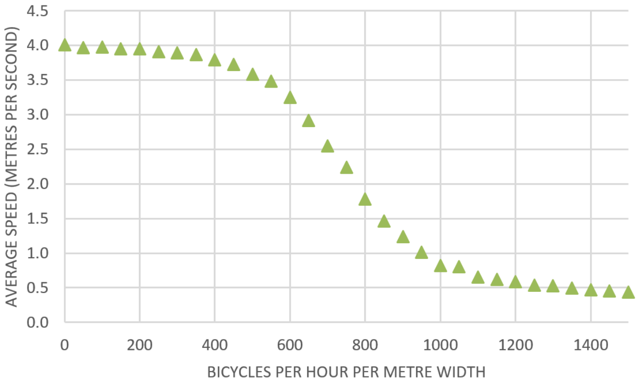
Figure 6: Crash proportions across a range of arrival rates for fixed and variable speed simulation runs



served. In this case, crash proportions are approximately zero until an inflection point is reached at approximately 550bpmph. A state change has occurred and the proportion of agents in a crashing state escalates rapidly (much more so than for fixed-speed operation). This corresponds with the visual observation of the simulation that congestion has occurred. The inflection point therefore indicates a capacity limit to the arrangement. Rather than the flow degrading slowly with increasing arrival, the flow degrades sharply. When this happens the shockwave propagates through the flow with dissipation only occurring once inflow to the area of breakdown has dropped sufficiently. This corresponds with equivalent observations of highway traffic and pedestrian traffic.

Exploring this further and plotting the average speed against this measure, Figure 7 is produced. This clearly demonstrates outputs in keeping with established three-phase traffic theory. Below inflow rates of approximately 500bpmph, speeds are high and close to the cyclists' desired speed. Once densities increase, and up to an inflow of approximately 1000bpmph, flow breakdown is increasingly likely. Beyond 1000bpmph, flow breakdown occurs consistently with average speeds being low. Be-

Figure 7: Average bicycle speeds across runs undertaken at given inflows



tween these two values, some runs will complete without flow breakdown, others will experience limited breakdown which resolves, and the remainder will experience flow breakdown which does not resolve. The balance between these three states depends on the inflow rate which, as it is stochastic in nature, means all three phases can potentially exist for a given parameter combination in different locations on the same path.

Breakdown tends to occur in the entry area, as inflow is not stopped if the inflow area is not clear. In essence, the bicycles are arriving from a notionally infinite width space into a fixed width one and consequently, a de facto bottleneck. Breakdown at the entry in this manner is paralleled in pedestrian behaviour, such as crowding around a door or at a corridor entrance (Hoogendoorn & Daamen, 2005).

The results of each parameter combination's set of runs is consequently bimodally distributed between those runs were speeds were high (i.e. no breakdown occurred) and where speeds were very low (i.e. breakdown was rapid and ongoing) as flow breakdown often takes substantial time to resolve (as in reality). The resulting plot (Figure 7) averages out that behavioural detail and thus it must be underlined that for a parameter combination such as at 750bpmph, few bicycles will be found travelling at 2.0ms^{-1} at any given time step — instead, this is an average of runs comprised mainly of slow/stopped bicycles and those travelling essentially unimpeded. The only variable between those runs is the stochastic nature of arrivals and therefore the occurrence of flow breakdown due to the 'noise' in the system, and in the absence of any exogenous factors, parallels real highway traffic behaviour. Similarly, no bicycle will be travelling at a speed less than their minimum but greater than zero (in a given time step), so indicated average speeds beyond 1000bpmph are results of the aggregation of stopped bicycles with those travelling at a speed greater than, in this case, 0.92ms^{-1}.

Given the inputs, it is important to note that the exact numbers observed are unimportant. However, the inputs to the simulation are based on first-principles and the limited literature that exists, and yield simulation outcomes in the range of values which are expected from that literature (Table 1): at the low end CROW (2007) specifies a comfortable capacity in the range of 75–187.5bpmph; at the high end, Navin (1994) computes a maximum capacity of 4000bpmph.

Most importantly however is the fundamental difference that is observed by the inclusion of speed-changing behaviour. Speed-changing behaviour is explicity ignored as an assumption in Botma (1995) but is shown here to result in a fundamental shift in outcomes within the range of values which a practitioner is likely to be concerned with.

6 Conclusions and Future Work

The lack of appropriate micro-scale bicycle modelling tools is a potential barrier to the assessment and quantification of schemes of various types. Such a barrier has been experienced by pedestrian scheme designers (and highway designers) in the past and the potential exists to utilise the basis of some successful pedestrian tools to produce models which are suitable for the modelling of bicycles. In addition, such bicycle models would have the obvious extension for interconnection with established pedestrian models and thus the modelling of more complex shared-space arrangements than is possible with current tools.

No literature exists establishing the behavioural traits of interacting cyclists and the limited literature that does exist is in disagreement by orders of magnitude over basic key values like infrastructure flow capacity. Similarly, empirical data of the scale necessary to establish these parameters are not available and are expensive to obtain. The clear next step of work from this paper is for practitioners to validate the theoretically-justified parameters and outcomes in the context of empirical data.

Work to deliver the Highway Capacity Manual took the work of Botma (1995) and folded those numbers into the fundamental level-of-service measure often used by highway designers. In the process, the caveats attached to any assumption in their production have been lost. However, we have shown here though a modified implementation of the Social Force Model (as first proposed by Helbing & Molnár, 1995) that the core assumption that the Botma (1995) paper is founded upon, results in a fundamental step-change in outputs within the range of values that capacity is considered.

There remains a wide range of research required in order to quantify cycle infrastructure. If there remains an aspiration to produce a robust modelling framework for cyclists (as, for example, the current wave of 'shared-space' research indicates is the case), then the underlying numerical basis must be similarly robust. Large-scale empirical data is required over a range of facilities, and similarly, large-scale studies of individual cycle behaviour are required over a range of demographics and nationalities. These do not currently exist in any form in the literature as they are resource-intensive to collect, however, if cycle modelling is to become as robust as motor vehicle modelling, then they are a necessity.

Acknowledgement

This work was financially supported by an EPSRC Doctoral Training Centre grant (EP/G03690X/1; http://www.epsrc.ac.uk) through the University of Southampton Institute for Complex Systems Simulation. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors also acknowledge the use of the IRIDIS High Performance Computing Facility (and its associated support services at the University of Southampton), upon which the presented simulations were run.

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