The importance of interactions in determining service measures for bicycles

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Abstract

The lack of agreed and objective measures for cycle service quality and capacity is an increasing barrier to the development of high-quality infrastructure. High cycle mode share jurisdictions face issues relating to increased cycle congestion whilst simultaneously, low cycle mode share jurisdictions face increasing calls for investment in cycle infrastructure, yet the ability to economically evaluate proposals is lacking. In both circumstances, a lack of robust quantitative measures is an issue.

The limited existing measures for cycle service quality are developed based on the "isolated cyclist" or on a general assumption of non-impedance. By contrast, the fundamental principles of highway traffic flow (and of pedestrian flow) are entirely predicated on the concept of the constituent interactions, with speed-flow/density-flow curves being a well-established and empirically verified result of this.

Consequently, to assess the importance of interactions between cyclists in service quality and capacity measures for bicycles, an agent-based 2D microsimulation and social-force model was developed to test the validity of the non-impedance assumptions for unidirectional flow. The ability of the bicycles to interact and change speed resulted in both qualitative and quantitatively different outcomes to non-interaction. The speed-changing interactions led to outcomes more in keeping with empirical data and experience; and with service quality degrading rapidly as capacity is approached in comparison to non-speed-changing behaviour where service quality changes relatively slowly.

The results from the simulation model therefore bring into question the validity of analysis that relies on isolated cyclists or non-interaction for use in quantitative measures. In particular, the non-linear increasing sensitivity of the quality of service as flow rates increase demonstrates the need to properly consider the interaction of the constituent bicycles in any realistic quantitative measure.

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1. Introduction

The related concepts of highway capacity and service quality have, in their current incarnation, informed road designers since the 1950s (e.g. Road Research Laboratory, 1965; Transportation Research Board, 2010). Whilst refinements have been made to the details of the measures over the intervening years, the core concepts have remained relatively static. For motor vehicles, the jamming density of traffic does not lead to the most efficient flow of vehicles as service quality degrades and flow breakdowns occur before the jamming density is reached. The same principles have also been long demonstrated as applicable to pedestrians (Fruin, 1971). In both cases, it is possible to quantitatively measure the degradation in driving (or crowding) conditions that occurs up to and beyond the optimum flow density. The resulting 'speed-flow'/'flow-density' curves, which reflect the impact of the interaction of the constituent users, are key to the basics of traffic engineering and find direct use in most macroscopic models (e.g. Atkins, 2013; Halcrow, n.d.). The Level of Service (LoS) measure[1], commonly used in the USA (American Association of State Highway and Transportation Officials, 2001), represents a categorical simplification of these principles. By contrast, the effect of the equivalent interactions for cycle flows, is poorly understood.

This paper presents the results of the development of a microsimulation model based upon the Social Force Model (SFM) developed by Helbing & Molnár (1995). This model has been used with great success in pedestrian modelling and forms the backbone of the major commercial packages currently used in industry (i.e. Legion and VisWalk). We propose that the basic components of the pedestrian SFM, are also likely applicable to cyclists. By aggregating basic aspects of the individual behaviour of cyclists from the literature, the model is used to demonstrate the impact of the assumptions underlying the (limited) current service quality measures for non-individual cyclists. Thereafter, by further application of reasonable cycle behaviour to the model (specifically, the ability to change speed in response to the surrounding presence of cyclists), speed-flow curves (and other emergent phenomena) are developed. This development of 'classic' speed-flow curves for cycles from a literature basis, and in a relatively simple model, indicate that an assumption of 'the isolated cyclist' cannot be used in the development of a robust quantitative measure for cycle quality of service.

2. Capacity and Service Quality

Despite the wide use of cycles substantially before the wide use of motor vehicles (e.g. Department for Transport, 2012), there are no robust quantitative measures for cycle user service quality in existence. In the UK and Europe, quality measures are informed by somewhat nebulous qualitative measures such as user comfort and satisfaction (CROW, 2007); whereas in the USA, attempts at quantitative measures and the development of a Level of Service (LoS) measure, are limited to the 'isolated cyclist' (perhaps representative of the generally low cycle rates in the USA; Barker et al., 2008). Limited US displays of a progressive attitude towards cycling (New York City Department of Transport, 2008) are focussed on the qualitative, as is also generally the case in the UK and Europe (City of Copenhagen, 2011; Greater London Authority, 2013). Even in those jurisdictions with some of the internationally highest cycle mode shares, the case for further infrastructure expansion is usually established almost exclusively through qualitative measures derived, at least in part, from user surveys (City of Copenhagen, 2011; CROW, 2007).

2.1. The Capacity of Cycle Infrastructure

There is a clear need for robust quantitative measures for cycle service quality. On the societal level, the value of cycling is established to hold a high cost-benefit ratio (CTC, 2013) but, save for (generally) limited national government support, cycle schemes and infrastructure are overwhelmingly delivered at the municipal or sub-regional level, where

[1] Levels of Service are a categorical "A to F" measure for the quality of service on a given stretch of highway; 'A' representing free-flow of a few vehicles and 'F' the other extreme of a solid/static traffic jam. See also, Section 2.2.

relatively immeasurable benefits – such as cost savings to national health care services – are essentially externalities and thus not captured in any local attempt to justify a scheme.

Establishing a quantitative measure by which highway (and/or pedestrian realm) schemes can be objectively measured and valued at the local level is dependent on the understanding of the capacity for constituent vehicles (and/or pedestrians). The continued development of quantitative tools such as Vissim (PTV, 2013a) and SATURN (Atkins, 2013), validation through use and the increases in available computer power have allowed the use of quantitative tools on all scales of highway/pedestrian scheme. Quantitative considerations are key to the UK transport planning process at the local scale (e.g. Transport for London, 2010) and, on a larger scale, through processes such as COBA (Department for Transport, 2004).

For bicycles however, the scale of data required to establish robust capacity measures is simply not available. The lack of reliable automated counters for cycle traffic, and the difficulty of accounting for homogeneous infrastructure and traffic flow, remains (amongst other reasons) a substantial barrier to the cost-effective collection of such data. Microscopically, pedestrian modelling has faced many of the same issues relating to data collection and simulation modelling tools such as Pedroute (Halcrow, n.d.), VisWalk (PTV, 2013b) and Legion (Legion Ltd., 2013) are widely used in industry to simulate and ex ante test the design of pedestrian spaces, and quantitatively assess the operation and/or safety critical aspects. Whilst Pedroute operates in a macroscopic manner based (originally) on detailed surveys of London Underground stations, VisWalk and Legion both operate on a microsimulation basis where the core understanding of pedestrian interaction is sufficient to build large and valid models.

In the literature considering the capacity of cycle infrastructure, there exists little data and where figures are available, they vary between sources by up to two orders of magnitude (Table 1).

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; NB. Comfort not absolute 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

2.2. Service Quality Measures for Traffic

For highway or pedestrian infrastructure, capacity cannot be defined as simply the maximum number of vehicles or pedestrians that can fit in given road space. For vehicles, this ultimate 'jamming density'[2] results in no movement ability for vehicles thus the overall flow rate is zero. At very low flow, vehicles have complete freedom to move, choose their speed and pass one another; at high flow rates this ability is

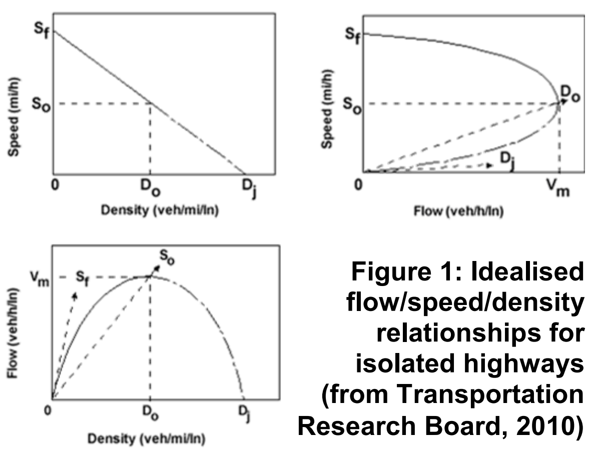


Figure 1: Idealised flow/speed/density relationships for isolated highways (from Transportation Research Board, 2010)

[2] The traffic density which is essentially 'solid' and in which no vehicle has freedom to move.

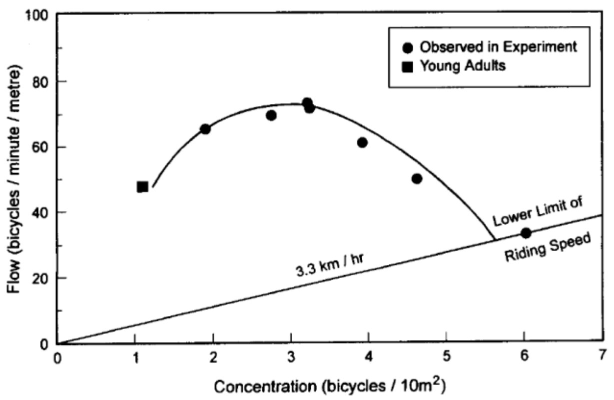
limited by the presence of other vehicles, with flow breakdown[3] increasingly likely. This resulting non-linear relationship between speed, density and flow, forms the foundation of traffic engineering (Transportation Research Board, 2010) and equivalent relationships have been shown to apply to pedestrians (Fruin, 1971). Figure 1 illustrates for (idealised) highway traffic.

The various measures that change across the range of flow – such as changes in speed, perceived driving conditions, flow density and ability to overtake – are considered as service quality measures and often (especially in the USA) summarised into the categorical 'A' to 'F' Level of Service (LoS) measure (Transportation Research Board, 2010).

2.3. Service Quality Measures for Bicycles

Section 2.1 noted the lack of capacity measures for even the most basic of bicycle infrastructure and as was mentioned, limited attempts have been made in the literature to establish both capacity and service quality measures. Limited work was undertaken by Navin (1994) involving a group of students under instruction to ride around a large radius loop "as fast as possible". Maximum flow was found at 14kmh^{-1} — here one should perhaps compare this with mean cycle speeds noted in Parkin & Rotheram (2010) who measured an empirical mean free speed of some 21.6kmh^{-1}. A flow-density curve was derived and is replicated in Figure 2.

Figure 2: Empirical results from Navin (1994)



This output from Navin (1994) demonstrates empirical resemblance to the lower component diagram of Figure 1; potentially establishing the applicability of the relevant traffic flow theories to bicycles. Also of note is a bound to the curve relating to the ability to maintain balance on the bicycle; such a bound does not apply to motor vehicles or pedestrians.

Navin (1994), being empirically derived, makes consideration of the variable Level of Service which exists between the isolated cyclist and a crowded one. However, the maximum capacity is derived based essentially on extrapolated close-contact 'packing' of the cyclists. Whilst this could represent a 'jamming density' in perhaps the absolute sense, real cyclists would be unlikely to arrange themselves in such a dense manner (especially laterally), even in times of complete flow breakdown. Therefore the capacity derived is perhaps unrealistic.

The only other literature relating to service quality (again by way of the Level of Service measure) is Botma (1995), which is especially important as it is the foundation for the bicycle Level of Service measure stated in the Highway Capacity Manual (the HCM; Transportation Research Board, 2010) and is thus potentially in use in the US and other international jurisdictions that derive their highway standards from the Green Book (American Association of State Highway and Transportation Officials, 2001) and/or HCM.

Botma considers the issue of bicycles interacting by considering the distribution of speeds and mathematically deriving the probabilities of passing another bicycle over a given distance. This is work derived from some of the historic Dutch standards (CROW, 1993) where a passing rate of ≤10% is considered acceptable. Botma considers this intuitively low (despite the fact the Dutch standards are both empirically-based and widely considered successful) and derives Levels of Service (LoS) based on various increasing rates of "hindrance"[4] up to a maximum of 100% at the LoS E/F threshold. Simultaneously, Botma makes the assumption that bicycles do not impede one another, even at the highest rates of passing. Whilst the derived service volumes are substantially lower than those proposed by

[3] Where speeds (and thus flows) drop to zero, i.e. a traffic jam.
[4] i.e. one-way passing (overtaking) or two-way 'meeting' events.

Navin (1994), this is a questionable assumption as it would only take one more than the available ‘virtual lane’ width of bicycle to simultaneous be engaged in a passing manoeuvre for either a collision, a departure from the carriageway or an avoidance speed change to occur. In any of those cases, clearly bicycle impedance would have occurred and in reality, bicycles would obviously take avoidance action.

3. The Social Force Model

If we are to test the validity of the literature assumption – i.e. does this intuitively obvious fact that cyclists impede one another only occur with a trivial frequency and thus the assumption is a valid simplification – then a method of modelling collision avoidance in a space is required.

Originally constructed by Helbing & Molnár (1995), the Social Force Model (SFM) 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, 2013b) and Legion (Legion Ltd., 2013) both depend on the principles established by Helbing & Molnár (VisWalk directly, and Legion by way of distillation in Still; 2000). Their wide use in industry has established the validity of the core models when, as with any model, properly calibrated.

The basis of the SFM is a vectoral ‘force-like’ quantity named the social force. As opposed a physical force, the social force is a metaphorical force which exists to quantify the “motivation to act”. The result, as is observable, is that pedestrians behave as if they were subject to an invisible force; namely, the social force. The social force experienced is the sum of all ‘forces’ exerted by other pedestrians (i.e. desire to not get too close to one another or conversely, for a group to stay together), by obstacles and boundaries, and by desire to head to a particular waypoint. Given the established validity for collective collision avoidance behaviour, the core of the SFM is adopted here and modelled bicycles will thus navigate a social force field. The mathematical details of the SFM, for brevity, are not replicated here from the original paper (Helbing & Molnár, 1995).

4. Model Design

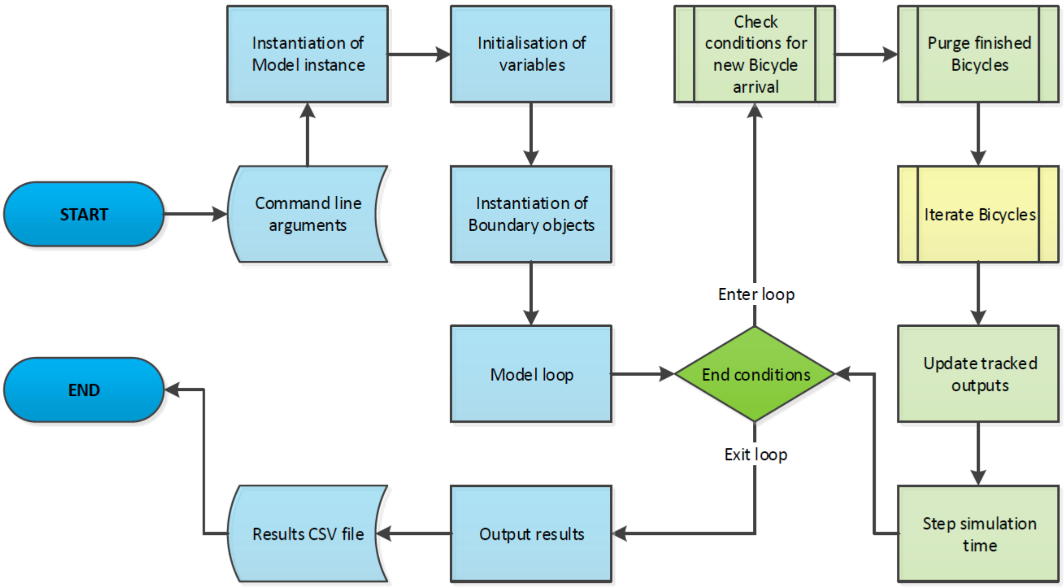
This paper presents a microsimulation model based upon the Social Force Model developed by Helbing & Molnár (1995), discussed above, and utilising other appropriate literature to ensure the characteristics intrinsic to cycling are properly represented.

The SFM is however, one aspect of the model, namely that relating to collision avoidance and path finding. The SFM itself is of no intrinsic use (save mathematically) without an implementation structure.

4.1. Model Implementation

The developed model utilises basic agent-based principles for the definition of bicycles. Bicycle objects make independent and individual decisions based on their own perception of the social force field surrounding them. Bicycles travel in two dimensional space, uni-directional flow and on a path of fixed width with parallel boundaries; i.e. the simplest form of cycle-only path. Decisions are therefore based solely on boundary avoidance and the avoidance of other bicycles. They are instantiated with Poisson-distributed arrival intervals according to overall parameter rate and purged once they have traversed the defined length. The overall model implementation is detailed in Figure 3.

Figure 3: Overarching model algorithm



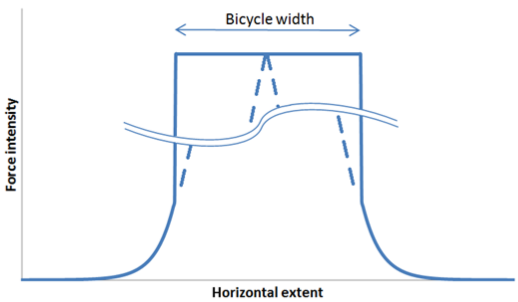
4.2. Social Force Generation

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 length equivalent to step length. Pedestrians themselves are point objects and are making decisions based on an instantaneous perception of the force field which notionally reflects the future arrangement in the force 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 sub-1s) then this starts to become less realistic. For bicycles, the definition of "sufficiently long" is likely to 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. Literature on acceleration rates for cyclists is of course limited but figures for acceleration of 0.8-1.2ms^{-2} and braking of 1.5ms^{-2} comfortable and 2.6ms^{-2} emergency, are quoted in design standards (CROW, 2007). Conversely, whilst not explored therein, it should be noted that empirical data in Parkin & Rotheram (2010) indicates acceleration rates significantly below those in the design standards with mean acceleration in the range of 0.2-0.3ms^{-2} for flat (or near-flat) gradients. Nonetheless, that was a small group study and consequently the values of acceleration from CROW (2007) of +1.0ms^{-2} and deceleration at -1.5ms^{-2} are used in the model, as these are likely to have the greatest empirical backing.

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 the force at the point which they currently occupy, but consider it at projected future locations based on the projection of where other bicycles will be at that time. Future force returns are discounted with increasing time to account for the uncertainty in future decisions of the other bicycles; essentially producing a 'net present force' on each considered path choice. Cyclists therefore navigate this force field, seeking vectors that minimise their overall exposure to repulsive force. To enable this, all force generating objects are registered on a 'ForceField object' and bicycles poll this in order to make their steering determinations; the 'ForceField' returning the sum of all forces (polling object excluded) at the given location.

Both boundary objects and bicycles have different force profile generation to the original SFM. Boundary exponential force distributions result in a model in which the balance of forces is sensitive to path width as the exponential distribution has infinite extent. To avoid this, and given that cyclist boundary effects are poorly understood, a simple linear function for force was used which decreases with distance from the wall and reaches zero at a distance of 0.5m (i.e. simulating kerb-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.

Figure 4 (left): Illustrative force profile for bicycles (for reference, notional internal exponential force profile is shown)



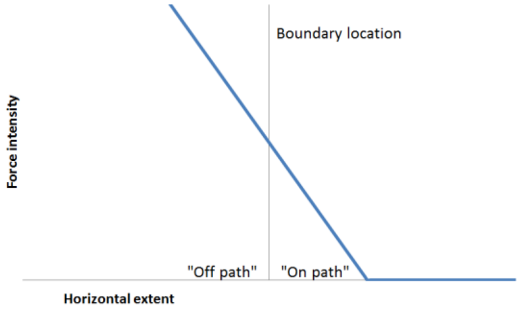


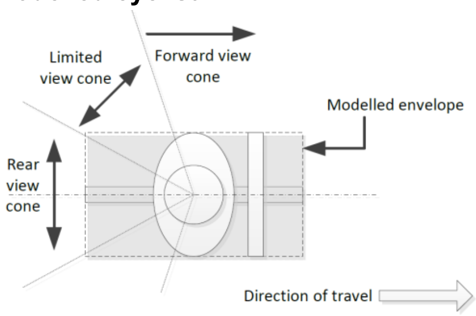
Figure 5 (right): Illustrative force profile for boundaries.

Bicycle force generation follows an exponential distribution akin to the original SFM but with an additional overlay reflecting the cyclist envelope. Pedestrians in the SFM are treated as point objects; by contrast, bicycles cannot compress one another (Helbing et al., 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 over the physical area of the bicycle. 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 reflecting the inappropriateness of a circular approximation for a bicycle/cyclist combination.

4.3. Force Perception Angle

The SFM considers a potential view-cone and Helbing & 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 & Molnár were primarily concerned with crowd crushes wherein pushing forces are explicitly non-trivial.

Figure 6: Proposed view cones for the modelled cyclist



For bicycles in ‘usual operation’, a simple reduction by half of other agents 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 whilst cycling than is the case for walking. Secondly, it is debatable whether a cyclist (or a pedestrian) would feel a pressure 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 the reduction factor, three different perception profiles are proposed (see Figure 6):

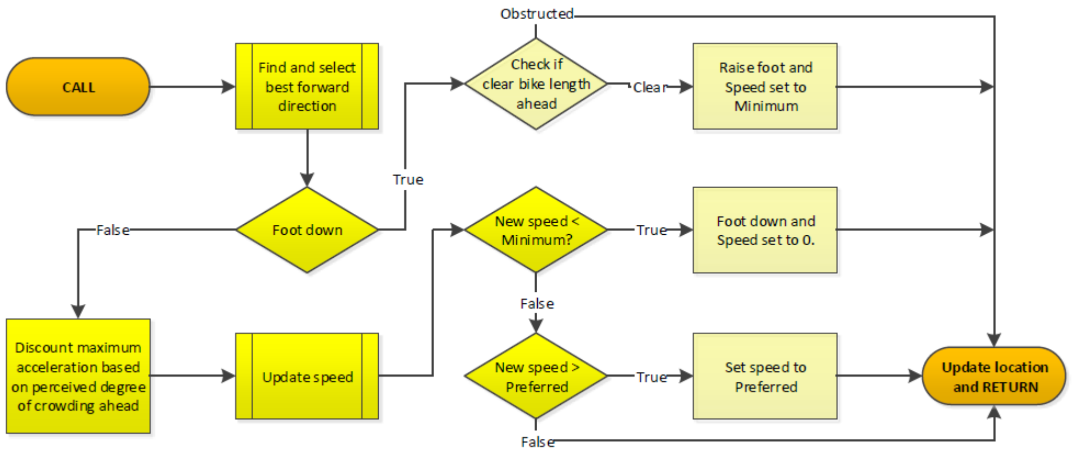
- If the perceived bicycle is within the forward view-cone (e.g. within ±100°), then the full force effect of that bicycle is perceived. This area requires no effort to view on behalf of the perceiving cyclist.
- If the perceived bicycle is within the side view-cone (e.g. within ±160° but not within ±100°) 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 that would be within these view-sectors is reduced.
- If the perceived bicycle is not within the side or front view-cones, (e.g. not within ±160°) then the cyclist would have to turn their head and torso simultaneously; a difficult task on a bicycle whilst maintaining full control. Consequently, these bicycles are perceived less the side view-cones (in this model, for simplicity, ignored entirely).

4.4. Bicycle Operation and Speed Selection

Finally, 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. Navin (2004) found empirically this minimum speed to be $3.3ms^{-1}$ ($0.9kmh^{-1}$, 2.1mph). CROW (2007) indicates that below a speed of $12kmh^{-1}$ ($3.3ms^{-1}$, 7.5mph), instability of the rider increases (though riding is still possible). In neither case is a distribution around these values available. Recognition of a minimum cycling speed is therefore also incorporated into the model.

Bicycles are instantiated with a desired speed drawn from a Normal distribution based on literature values (CROW, 2007) and with Poisson distributed arrival intervals for the given rate of arrival. Bicycles are removed from the pathway after a fixed distance. Each bicycle is iterated according to the loop detailed in Figure 7.

Figure 7: Bicycle iteraton algorithm



Bicycles iterate by first establishing the projected repulsive force at each time step forward and discounted exponentially against increasing time (reflecting uncertainty) to a ‘net present force’. The direction with the lowest overall discounted repulsive force is chosen. For simplicity, a unitary exponential discount was used.

Bicycle speed selection is achieved by first defining two states: that of “foot down” and “foot up”. Should the cyclist have their foot down then the consideration is simply if they can move into the space immediately in front of them; if clear, then the foot is raised and the speed set to the minimum sustainable. This parallels shuffling behaviour of pedestrians and allows a group of cyclists to `bunch up', as for example, would happen at signals.

Alternatively, if the cyclist has their foot up – i.e. they're travelling faster than the minimum sustainable speed – then the positive acceleration (capped positive and negatively by literature values; CROW, 2007) is reduced based on the overall force on the chosen vector which, if sufficient, results in deceleration and thus slowing. Resulting speeds are capped at the desired maximum and by the minimum sustainable (which if the speed would fall below, the `foot down' state is activated).

Speed changes are therefore made in a parallel manner to the SFM in that the perceived force results in a change in speed (note speed not velocity, as speed and direction have been decoupled in this model). However, force perception is that on the chosen vector thus the cyclist is, more realistically, making determinations based on a perceived future situation and not a current instantaneous measure.

Finally, once direction and speed selection have taken place, spatial location is updated. The model iterates through every bicycle once per time step. Visual inspection allowed validation to ensure the model was behaving as expected in so far as bicycles react appropriately to obstacles and to one another.

4.5. Model Parameters

A number of parameters are necessary to operate the model (Table 2). The parameter space explored for the model exists in two-dimensions defined by path width and bicycle arrival rate. All other parameters remain constant between runs.

Table 2: Model parameters

Parameter	Value	Parameter	Value
Simulation length	300.0s (0.1s step)	Bicycle maximum deceleration (CROW, 2007)	$-1.5ms^{-2}$
Bicycle traversal length	75.0m	Bicycle min. speed (Navin, 1994)	$0.92ms^{-1}$
Boundary force spread	500	Bicycle maximum steering angle	40°
Boundary force scaling	10000	Bicycle steering step	4.0°
Bicycle force spread	75	Bicycle forward planning step	0.25s
Bicycle force scaling	375	Bicycle fwd. max. planning time	5.0s
Bicycle force ellipse foci dist.	5000mm	Bicycle fwd. planning decay const	1.0
Bicycle width	750mm	Bicycle angle of sight	100°
Bicycle length	1800mm	Bicycle angle of reduced sight	160°
Bicycle speed mean and standard dev. (CROW, 2007)	$\mu=4.02ms^{-1}$ $\sigma=0.21ms^{-1}$	Crowding reaction factor	0.4
Bicycle maximum acceleration (CROW, 2007)	$+1.0ms^{-2}$	Side (rear) reaction factor	0.1 (0.0)

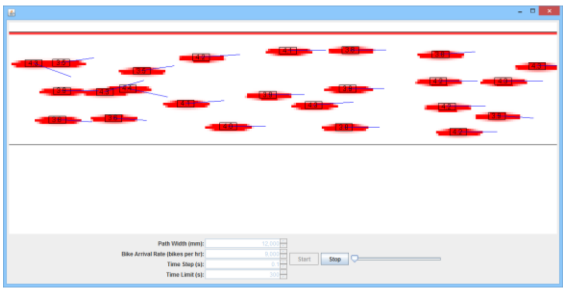
4.6. Model Outputs

Model outputs are recorded to files and have been retained for analysis. Recording is also made of random seed variables for full reproducibility. Primary outputs are recorded as follows:

- Average proportion of bicycles experiencing a crash condition: i.e. intersection with another bicycle, boundary or off-path area;
- Average distance to the nearest bicycle: in essence, a measure of density; and
- Average speed of bicycles.

Outputs are recorded for each run and for the results presented in this paper, runs were undertaken 25 times per parameter combination.

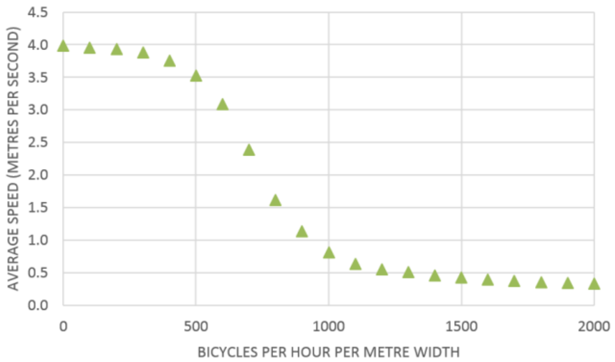
Figure 8: Demonstration of model graphical user interface



5. Results

The primary design purpose of the model is to assess the validity of the non-interference assumption for bicycles. The basic concept of interference is obviously intuitive however this does not necessarily render the assumption invalid, potentially only a simplification necessary for modelling. Therefore, should the assumption be a valid simplification, one would expect there to be a trivial (or indeed zero) rate of bicycle collisions within the range of values quoted in Botma (1995) and consequently informing the Levels of Service in the Highway Capacity Manual. Given that any non-trivial rate of collisions would result in an unacceptable user experience, findings of substantial collisions would render the use of the proposed range of values for good to medium Levels of Service to be invalid.

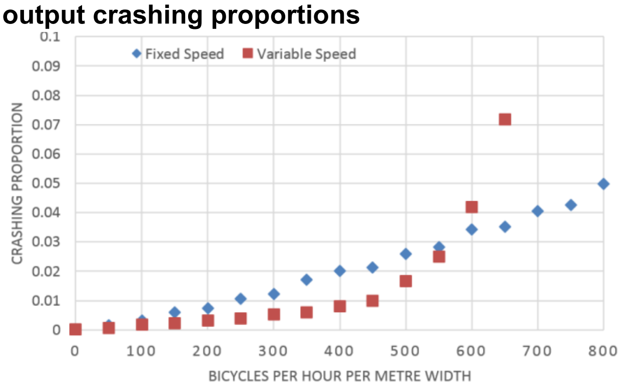
Figure 9: Plot of model-derived speed-flow curve



The model was run across a range of path widths and a range of bicycle arrival rates, both with and without the ability of bicycles to impede one another. A plot of bicycle speeds against arrival rate (Figure 9) results in a 'classic' speed-flow curve. This confirms that the model is, to some extent, producing valid behaviour that correlates qualitatively with experience and empirical data from Navin (1994). Speeds remain relatively unconstrained until approaching 500bphpm where they begin to degrade progressively more rapidly before dropping, on average, below the minimum sustainable (0.9ms^{-1} from Navin, 1994) at approx. 900bphpm before levelling off at about 0.3ms^{-1} (note this is possible as some bicycles are static and some will be moving at a low speed).

Speed selection behaviour and differential directional perception were removed from the model. This provides the closest replication of the core assumption in Botma (1995). The removal of directional perception gives the greatest opportunity for bicycles to get out of one another's way and avoid collisions and thus would be an absolute best case for validating the assumption. Following the runs, parameter combinations were normalised to a combined bicycles per hour per metre of width measure. Figure 10 illustrates the results.

Figure 10: Low range comparison of model output crashing proportions



As the rate of bicycle arrival increases, as expected, the rate of crashing increases. In both cases, higher than approximately 600 bicycles per hour per metre width (bphpm) arrival rate, crash rates begin to increase to a non-trivial level. For the fixed speed model, this happens gradually reaching 10% of bicycles experiencing a collision at 1100bphpm (though clearly the situation would be unacceptable long before 10% was reached). For the (more realistic) variable speed model, at around 600bphpm, collision rates start to increase very rapidly reaching 10% before approx. 700bphpm. Both have negligible collision rates below 500bphpm.

Comparison of Figures 9 and 10 indicates that the rapid increase in crashes recorded is closely tied with the fall in average bicycle speeds. Graphical inspection of the model indicates the mode of flow breakdown is generally a multi-bicycle collision occurring after the point of instantiation. This is expected as the entry into the model is effectively a bottleneck (from infinite width to fixed-width space) and instantiation is not slowed if there is not space into which the bicycles can arrive. This correlates with work relating to pedestrian bottlenecks (Hoogendoorn & Daamen, 2005). The area of the speed-flow curve where average speeds degrade is characterised by a bimodal spread of simulation results (for a given parameter pair) between those runs in which flow does not breakdown and those in which it does. The only variable between these circumstances is the stochastic variation of instantiation. In this sense, this parallels highway traffic where flow breakdown can occur due to the ‘noise’ in the system in the absence of any exogenous factors.

5.1. Comparison to Literature Values

Table 1 summarised the literature capacity rates. At the low end, CROW (2007) specifies a comfortable capacity in the range 75-187.5bphpm; at the high end, Navin (1994) extrapolated a capacity of 4000bphpm. The model outputs indicate that capacity (i.e. where service quality collapses in a step-change/flow-breakdown manner) is within the range bound by these values at approximately 500-600bphpm. Given it is a comfort value, the CROW value is perhaps most appropriate as a design aim however the actual capacity of infrastructure is indicatively higher by between 3 and 8 times. By contrast, the Navin (1994) value of 4000bphpm and the Vejdirektoratet (2012) value of 1000-1500bphpm are potentially excessive by an order of magnitude.

Interestingly, the degradation of speeds and increase in crash rate occurs at roughly the same values indicated as a maximum by Botma (1995). This is likely coincidental given the method of their derivation and in any case, would be relatively arbitrary if instead defined in a circumstances where crashes could not be ignored given the smooth increase in crashing rates with arrival rates. If even a few percent of crashes is considered unacceptable (given the model instantiation function, one would expect rates close to but not necessarily equal to zero for all arrival rates), it is worth noting that under fixed-speed non-interaction, crash rates increase over 1% by 250bphpm whereas stay below 1% up to 450bphpm for variable-speed bicycles (Figure 10). This, and the visually clear qualitative difference, indicates that the interaction of bicycles is key at lower flow ranges likely to be most commonly experienced.

6. Conclusions

A detailed review of the literature indicates that there exists neither a robust measure for bicycle infrastructure capacity, nor for service quality; so consequently no real ability to economically evaluate schemes. Literature across jurisdictions is variable in detail and quantitative values with figures quoted are often historically static and show conspicuously low precision, indicative of a lack of research-based foundation. Tracing the source of various quantitative measures through the literature usually leads to a mathematical calculation of the physical capacity of a space given simply the dimensions of that space and of a bicycle. There is an inherent assumption in this that the infrastructure can operate in a satisfactory manner up to this capacity. The only widely used measure where service quality varies below the ultimate capacity, that was proposed in Botma (1995) and entrained in the Highway Capacity Manual (Transportation Research Board, 2010), assumes non-impedance of bicycles and thus approaches the same assumption from an alternative viewpoint.

A simple agent-based 2D microsimulation model based on the Social Force Model (Helbing and Molnár, 1995) was constructed to test the validity of this assumption. The results from the model demonstrate that the assumption of non-impedance results in a qualitatively different experience for the cyclist as arrival rates increase. Without impedance (i.e. using the assumptions in Botma, 1995), crashing rates increase steadily, passing 1% at 250bphpm. By contrast, a qualitatively and quantitatively different outcome results from the inclusion of speed selection behaviour which is more in keeping with basic traffic flow theory and empirical research. A 1% crash rate is not passed until 450bphpm and then crashes increase dramatically giving a sudden degradation in service for end users (indicative of flow breakdown) and a fundamental change in flow regime between acceptable and unacceptable. Consequently, if it is desired to begin to utilise robust quantitative tools to value bicycle infrastructure schemes, the interaction of the bicycles cannot realistically be ignored for non-trivial rates of flow.

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