Australasian Transport Research Forum 2023 Proceedings
29 November – 1 December, Perth, Australia
Publication website: http://www.atrf.info

Enhancing the modelling of shared spaces: Evolution of the Social Force Model

Delilah Slack-Smith[1], Kasun Wijayaratna[2], Michelle Zeibots[3]

[1,2,3]Transport Research Centre, School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology, University of Technology Sydney

Email for correspondence (presenting author): Delilah.G.Slack-Smith@student.uts.edu.au

Abstract

The creation of shared road infrastructure is becoming increasingly important, due to the value of enhancing traffic management and the social and economic aspects of a community. To that end, the paper has considered relevant literature with an emphasis on modelling pedestrians and vehicles in the context of shared road infrastructure. This literature has included publications related to pedestrian modelling and vehicle modelling, as well as literature dedicated to shared spaces in particular.

Previous pedestrian models have supported interactions between pedestrians and other pedestrians and static obstacles. At least one model has also integrated an activity model, which would enable a shared space model to better model real human behaviour and improve its accuracy. Previous vehicle modelling literature has described methods to model interactions between vehicles and other vehicles and pedestrians at marked crossings.

Most or all shared space microscopic models integrate a social force model and a car-following model. The major differences between previous shared space models concern interactions between vehicles and pedestrians, but the conditions under which particular long-range conflict avoidance tactics and strategies are applicable to different classes of agents needs more research.

This paper describes a novel model structure to support and enhance the evaluation of shared space designs prior to implementation, and predict the effect of redesigning pre-existing shared spaces. An adapted social force model has been developed to describe and visualise shared road infrastructure, especially shared spaces with an absence of separating infrastructure between users, and to output metrics that can be used in conjunction with the latest evaluation approaches.

1. Introduction

Road transport networks are experiencing increasing levels of congestion resulting from urbanisation and population growth. Consequently, neighbourhoods within and around those networks are lacking a sense of place and community identity (Hamilton-Baillie 2008).

Most past attempts to mitigate congestion have developed and implemented strategies that increase the capacity of the infrastructure. These approaches have resulted in induced demand (Zeibots 2007) and thus exacerbated congestion issues. Alternative strategies have focussed on reducing demand by making public and active transport more available and accessible.

In addition, a number of cities are promoting the reclamation of streets by pedestrians and increasing support for community spaces through the definition of places. In NSW, the

Movement and Place framework (*e.g.* "Aligning Movement and Place" 2022) includes discussion of this sentiment and its incorporation within strategic planning objectives. This shift in planning focus can emphasise novel designs which encourage shared road infrastructure. Wijayaratna *et al.* (2022) summarises the properties which define shared road infrastructure. These include granting equal priority to cars and other transport modes. This is achieved by reducing car speeds and car use and advocating for active and public transport. It also distinguishes between "**traffic calming"** and "**shared space designs"**. Traffic calming slows vehicles while maintaining segregation between transport modes where shared space designs integrates the transport modes and removes barriers between them.

Table 1: Mathematical Glossary

Agent Properties	Description	Relationship Properties	Description
$\alpha \in A$	Agent	$\beta \in A - \{\alpha\}$	Counteragent
$\boldsymbol{x}_\alpha^*(t)$	Desired position	$\zeta \in Z$	Zone
$\boldsymbol{x}_\alpha(t)$	Current position	$\omega \in \Omega \subseteq Z$	Obstacle
v_α^{pref}	Preferred speed	$\nu \in N$	Node
$v_\alpha^*(t)$	Desired speed	$d(\boldsymbol{x}, \boldsymbol{y}) = \lVert \boldsymbol{x} - \boldsymbol{y} \rVert = \sqrt{(\boldsymbol{x} - \boldsymbol{y})^2}$	Distance function
$\hat{\boldsymbol{e}}_\alpha^*(t)$	Desired direction	$\boldsymbol{x}_U(\boldsymbol{x}_\alpha) = \mathrm{argmin}_{x \in X_U}[d^2(\boldsymbol{x}, \boldsymbol{x}_\alpha)] \exists U \in \{\zeta, \nu\}$	Nearest point
$\boldsymbol{v}_\alpha^*(t) = v_\alpha^*(t) \hat{\boldsymbol{e}}_\alpha^*(t)$	Desired velocity	$\boldsymbol{x}_{\alpha U} = \boldsymbol{x}_U - \boldsymbol{x}_\alpha \exists U \in \{\beta, \zeta, \nu\}$	Relative position
$\boldsymbol{v}_\alpha(t)$	Current velocity	$d_{\alpha U =} d(\boldsymbol{x}_U, \boldsymbol{x}_\alpha) \exists U \in \{\beta, \zeta, \nu\}$	Relative distance
$\hat{\boldsymbol{e}}_\alpha = \frac{\boldsymbol{v}_\alpha}{\lVert \boldsymbol{v}_\alpha \rVert}$	Current direction	$\hat{\boldsymbol{e}}_{\alpha U} = \frac{\boldsymbol{x}_{\alpha U}}{\lVert \boldsymbol{x}_{\alpha U} \rVert}$	Relative direction
l_α, w_α	Length and width	$\hat{\boldsymbol{n}}_{\alpha U} = -\hat{\boldsymbol{e}}_{\alpha U}$	Unit normal
$s_\alpha^*(t)$	Preferred netto (bumper-to-bumper) distance	$\hat{\boldsymbol{t}}_{\alpha U} = \hat{\boldsymbol{n}}_{\alpha U}^{\perp}$	Unit tangent
$s_\alpha(t) = x_{\alpha-1} - x_\alpha - l_{\alpha-1}$	Current netto distance	$\boldsymbol{v}_{\alpha\beta} = \boldsymbol{v}_\beta - \boldsymbol{v}_\alpha$	Relative velocity
$\Delta v_\alpha = v_\alpha - v_{\alpha-1}$	Excess speed	$r_\alpha(\boldsymbol{x}_{\alpha\beta})$	Effective radius
$\Theta(\mathrm{h}) = \begin{cases} 1\ \forall h > 0 \\ 0 \text{ otherwise} \end{cases}$	Heaviside function	$r_{\alpha\beta}(\boldsymbol{x}_{\alpha\beta}) = r_\alpha(\boldsymbol{x}_{\alpha\beta}) + r_\beta(-\boldsymbol{x}_{\alpha\beta})$	Sum of radii
$E[\boldsymbol{x}_\alpha(t)]$	Expected (future) position	$A_{\alpha U} \exists U \in \{\beta, \zeta\}$	Magnitude
		$D_{\alpha U} \exists U \in \{\beta, \zeta\}$	Characteristic Distance

Table 1 presents key mathematical notation that will be used throughout this paper when discussing agents and their relationships (spatial and otherwise) with counteragents (*i.e.* other agents) and with zones and nodes.

Shared space designs have some safety challenges but also present some opportunities for safety improvements. and perceived safety challenges (*q.v.* p. 27 of Wijayaratna *et al.* (2022) for further details). Since higher speeds are correlated with more pedestrian fatalities, slower speeds are required for shared spaces. In addition, shared spaces often place vegetation and street furniture strategically to create safe zones for more vulnerable pedestrians.

These two trends, more public and active transport and more shared infrastructure, result in complex multimodal road networks. These networks are more challenging to operate from an efficiency as well as a safety perspective. It is therefore important that practitioners can access modelling tools that accurately capture the behaviour of transport users in multimodal environments.

To that end, this paper examines existing modelling techniques that capture behaviour in shared road environments to identify gaps and areas of future research. Furthermore, the paper proposes a novel modelling framework to address these gaps and enhance the realism of the shared road infrastructure modelling.

2. Examination of existing knowledge

Shared space literature contains research presenting design options (Federal Highway Administration 2017), planning strategies (Auckland City Council 2017), and case study analysis of implementations (Firth 2011). However, the focus of this paper is to understand the evolution of literature concerning the modelling and prediction of performance of shared road infrastructure. Accordingly, to improve upon previous research, it is necessary to complete a focussed review of this specific modelling domain.

This literature includes articles on vehicle modelling, pedestrian modelling, and shared space modelling. Most if not all existing shared space models incorporate techniques previously used to model pedestrians and vehicles. In addition to extending modelling techniques previously applied to shared spaces and project-specific innovations, model enhancements arising from pedestrian and vehicle traffic modelling are equally relevant to shared spaces.

Whereas standard road infrastructure can largely be modelled with independent models of pedestrian and vehicle behaviour, shared spaces must model interdependent pedestrian and vehicle behaviour.

The following sections will detail relevant modelling literature related to shared spaces, divided into: pedestrian modelling literature, vehicle modelling literature, and literature specifically related to modelling shared space modelling.

2.1. Pedestrian modelling literature

Figure 1: Pedestrian Modelling Literature

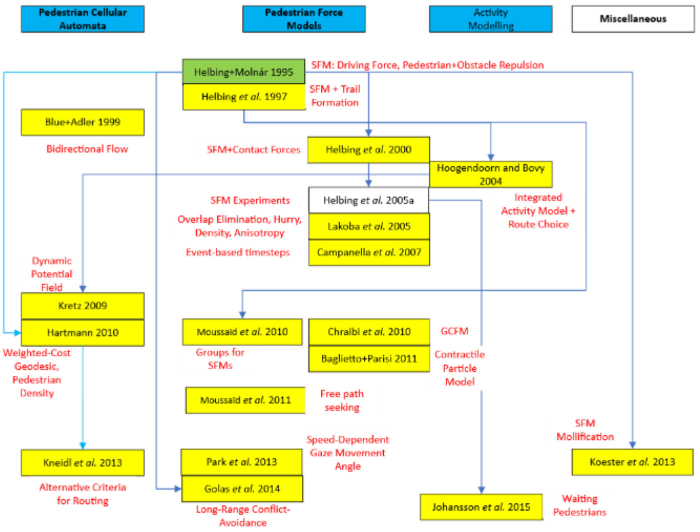


Figure 1 illustrates relationships between the pedestrian modelling literature most relevant to microscopic shared space modelling. This literature includes microscopic models of pedestrian behaviour and literature describing elements with the potential to enhance a microscopic model, pedestrian or otherwise.

Microscopic models analyse the behaviour of individual agents, i.e. self-directed physical particles. Macroscopic models model the behaviour of larger groups of agents by treating it as a fluid dynamics problem. Mesoscopic models occupy an intermediate position between the other two kinds of models.

2.1.1. Macroscopic

Fruin (1970) presented measurements of pedestrian attributes and behavior in queues and stairways, discussed the psychology of personal space, and proposed a level-of-service framework for pedestrians. Other aspects of macroscopic modelling such as the fundamental diagram have been investigated in other work (Saberi and Mahmassani 2014)

Macroscopic models can be used to validate high-level properties emerging from microscopic models and have been used to enhance microscopic pedestrian models (Golas *et al.* 2014). For shared spaces in particular, macroscopic pedestrian models may be useful to efficiently model inter-agent reactions at longer ranges.

2.1.2. Microscopic

The two most common approaches to microscopic modelling are cellular automata models and force models such as the social force model.

Cellular automata (Blue and Adler 1999) are discretised in space and time and are simple and efficient to support large numbers of homogeneous agents. In addition, they have been extended to support a dynamic potential field for travel-cost (Kretz 2009, Hartmann 2010) and to support a multilevel pedestrian model with multiple routing criteria (Kneidl *et al.* 2013, etc.), allowing density-dependent path choice and diverse preferences to be supported efficiently. Unfortunately, cellular automata would be difficult to extend to multiple classes of agent with different sizes, speeds, and handling properties which differ by orders of magnitude.

Force models on the other hand support heterogeneous pedestrian agents without introducing undue complexity. The most well-known physical model used for microscopic modelling of pedestrians is the social force model (SFM), proposed by Helbing and Molnár (1995), which defines a stochastic differential equation system presented in Eqn. 1:

$$\boldsymbol{F}_{\alpha}^{\text{total}} = \boldsymbol{f}_{\alpha}^{\text{drive}} + \sum_{\beta \neq \alpha} \boldsymbol{f}_{\alpha\beta}^{\text{soc}} + \sum_{\omega} \boldsymbol{f}_{\alpha\omega}^{\text{soc}} + \sum_{U} \boldsymbol{f}_{\alpha U}^{\text{att}} + \boldsymbol{\xi}_{\alpha}$$
$$\dot{\boldsymbol{w}}_{\alpha} = \boldsymbol{F}_{\alpha}^{\text{total}}$$
$$\dot{\boldsymbol{x}}_{\alpha} = \mathbf{v}_{\alpha} = \min\left(\mathrm{v}_{\alpha}^{\text{pref}}, \mathrm{w}_{\alpha}\right) \hat{\boldsymbol{e}}_{\alpha} [\text{Note: } w_{\alpha} \hat{\boldsymbol{e}}_{\alpha} = \boldsymbol{w}_{\alpha}, w_{\alpha} \geq 0]$$

Equation 1: SFM (Social Force Model) equation

where:
$\boldsymbol{f}_{\alpha}^{\text{drive}} = \frac{v_{\alpha}^{*} - v_{\alpha}}{T_{\text{relax}}}$ [driving force], $\boldsymbol{f}_{\alpha U}^{\text{soc}}\ \forall U \in \{\beta, \omega\}$ and $\boldsymbol{f}_{\alpha U}^{\text{att}} \forall U \in \{\beta, \omega\}$ are repulsions from and attractions to other pedestrians and objects, and $\boldsymbol{\xi}_{\alpha}$ is a stochastic fluctuation vector.

Force models such as the SFM offer a flexible microscopic transport model for pedestrians. They have been extended to handle high-density high-urgency scenarios (*e.g.* evacuation) with contact forces, panic, and herding behaviour (Helbing *et al.* 2000):

$$m_{\alpha} \dot{\boldsymbol{v}}_{\alpha} = \frac{m_{\alpha}(\boldsymbol{v}_{\alpha}^{*} - \boldsymbol{v}_{\alpha})}{\tau} + \sum_{\beta \neq \alpha} \boldsymbol{f}_{\alpha\beta}^{\text{soc}} + \sum_{\beta \neq \alpha} \boldsymbol{f}_{\alpha\beta}^{\text{phys}} + \sum_{\omega} \boldsymbol{f}_{\alpha\omega}^{\text{soc}} + \sum_{\omega} \boldsymbol{f}_{\alpha\omega}^{\text{phys}}$$
$$\boldsymbol{f}_{\alpha\beta}^{\text{phys}} = k\Theta(r_{\alpha\beta} - d_{\alpha\beta})\hat{\boldsymbol{n}}_{\alpha\beta} + \kappa\Theta(r_{\alpha\beta} - d_{\alpha\beta})(\boldsymbol{v}_{\alpha\beta} \cdot \hat{\boldsymbol{t}}_{\alpha\beta})\hat{\boldsymbol{t}}_{\alpha\beta}$$

Equation 2: SFM equation with normal and tangential contact forces

Other extensions for high-density pedestrian modelling have included using adaptive timesteps as part of a collision-detection and -avoidance strategy (Lakoba et al. 2005, Campanella et al. 2007), and the use of elastically deforming overlapping agents (Chraibi *et al.* 2010, Baglietto and Parisi 2011). They have since been extended to proactively seek a clear path between other agents instead of reacting to social pressure (Moussaïd *et al.* 2011). They have also been extended to support waiting pedestrians (Johansson *et al.* 2015), which may be useful to describe *place* aspects of a shared space. Chen *et al.* (2018) also compare numerous social force models of pedestrians in more detail.
In addition to the literature extending the social force model, Köster *et al.* (2013) sought to analyse and improve its numerical stability by substituting discontinuous functions with continuous functions whenever practicable. The numerical techniques they have applied to the SFM are applicable to other transport modes and microscopic shared space models in particular.

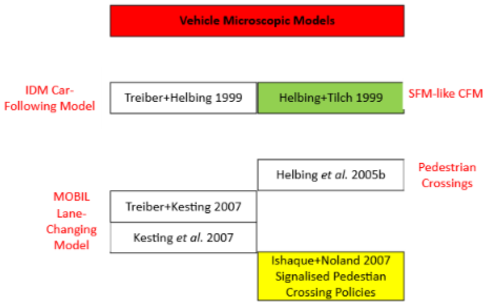
2.1.3. Mesoscopic

Mesoscopic models serve as the middle ground between macroscopic models and the more detailed microsimulation models and can incorporate aspects of both (Roads and Maritime Services 2013). Hoogendoorn and Bovy (2004) implements an aggregate approximation to a social force model and integrates an activity model to model foot traffic near Schiphol, which reflects a mesoscopic approach to capture high-level information about traffic flow through the area. Kneidl *et al.* (2013) describes a multilayer model combining three different routing criteria (fastest path, air-line approximation, and simple and longest leg (SALL)) and a cellular automata model. Integrating an activity model and/or improved routing criteria into a shared space model would better model real human behaviour and improve its accuracy.

2.2. Vehicle modelling literature

Because shared spaces contain vehicles as well as pedestrians, vehicle modelling literature is also relevant and relevant. Figure 2 illustrates relationships, chronological and genealogical, between vehicle modelling literature relevant to shared space modelling. This literature describes both: prior approaches to describe inter-vehicular forces; and prior approaches to forces between vehicles and pedestrians at marked crossings, signalised or otherwise.

Figure 2: Vehicle Modelling Literature



The social force model (Helbing and Molnár 1995) has been used as the basis for a microscopic car-following model called the generalised force model (Helbing and Tilch 1999):

$$\begin{aligned}\dot{v_\alpha} &= f_\alpha^0(v_\alpha) + \sum_{\beta\neq\alpha} f_{\alpha\beta}\left(x_\alpha, v_\alpha; x_\beta, v_\beta\right) + \xi_\alpha \\ &\cong \frac{v_\alpha^* - v_\alpha}{T_{\text{accel}}} + f_{\alpha,\alpha-1}(x_\alpha, v_\alpha; x_{\alpha-1}, v_{\alpha-1}) \\ &\cong \frac{v_\alpha^* - v_\alpha}{T_{\text{accel}}} - \frac{\Delta v_\alpha \Theta(\Delta v_\alpha)}{T_{\text{brake}}} \exp\left[-\frac{s_\alpha - s^*(v_\alpha)}{R_{\text{brake}}}\right]\end{aligned}$$

Equation 3: Generalised force model (GFM)

where:

$$\begin{aligned}s^*(v_\alpha) &= d_\alpha^{\text{safe}} + T_{\text{react}} v_\alpha \\ v_\alpha^* &= \left[1 - \exp\left(-\frac{s_\alpha - s_\alpha^*}{R_{\text{accel}}}\right)\right] v_\alpha^{\text{pref}}\end{aligned}$$

yielding a model with two social forces acting on each car: one which causes the car to slow down if the leading vehicle is moving more slowly; and one which should cause cars to converge to their desired speed in the absence of leading vehicles. The authors compared it to state-of-the-art car-following models of the time.

It is interesting to compare it to the Intelligent Driver Model (IDM), proposed by Treiber and Helbing (1999):

$$\dot{v}_\alpha = a\left[1 - \left(\frac{v_\alpha}{v_\alpha^0}\right)^\delta - \left(\frac{s^*}{s_\alpha}\right)^2\right] \exists \delta \text{ s.t. } 1 \leq \delta \leq 5 \text{ [usually 4]}$$

Equation 4:Intelligent Driver Model (IDM)

where $s^*(\mathrm{v}_\alpha, \Delta\mathrm{v}_\alpha) = d_\alpha^{\text{safe}} + \max\left(\frac{v_\alpha \Delta v_\alpha}{2\sqrt{ab}}, 0\right)$, a, b are the maximum comfortable acceleration and deceleration of the vehicle, and v_α^0 is the preferred speed of the vehicle or the agent driving it. The IDM has been further developed in subsequent papers (Kesting *et al.* 2010).

In addition, previous literature has modelled pedestrian crossings (Helbing *et al.* 2005b, Ishaque and Noland 2007) and lane-changing (Treiber and Kesting 2007, Kesting *et al.* 2007). In order to compare shared space designs to non-shared space designs, pedestrian crossing modelling is very relevant and lane-changing could be relevant for some shared space designs.

A genealogical literature review (van Wageningen-Kessels *et al.* 2015) discusses in detail the strengths and limitations of many more methods for modelling traffic flow, which could also be relevant to modelling inter-vehicular interactions in shared spaces.

2.3. Shared space modelling literature

Figure 3: Shared Space Modelling Literature

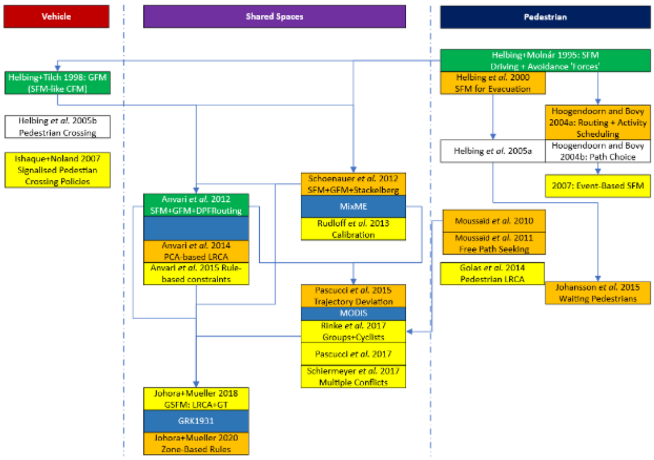


Figure 3 presents relevant shared space modelling literature that includes a rigorous presentation of methodology and can be replicated and enhanced in future modelling applications and Table 2 compares the salient features of these models.

Table 2: Shared Space Model Features

	Social Force Components (Driving, Social, Follow, Obstacle, Infrastructure Guidance)	**Physical Forces (Social, Obstacle)**	**Transport Modes (Pedestrian, Cyclist, Motorist)**	**Longer Timescale (Free-path seeking, Game-theoy, CDCR, Clustering, Deviation, Macroscopic)**	**Improved Prediction (PCA, Nonlinear)**	**Multiple Conflict LRCA**	**Zones (Guidance, Potential, Repulsion, Rules)**	**Physical Constraints (Steering)**
(SFM) Helbing and Molnár 1995	DSO		P					
(GFM) Helbing and Tilch 1998	**DSF**		M					
(SFM-Evac) Helbing *et al.* 2000	DSO	**SO**	P					
Moussaïd *et al.* 2010	DSO		**PG**					
Moussaïd *et al.* 2011	**D**	SO	P	**FPS**		**Y**		
Moussaïd *et al.* 2010	DSO		**PG**					
Schönauer *et al.* 2012 (MixME)	**DSFOI**		**PM**	**GT**			**G**	Y
Rudloff *et al.* 2013 (MixME)	DSFOI		PM	GT		Y	G	Y
Anvari *et al.* (2012)	DSFO		PM					**Y**

Golas *et al.* 2014	DSO		P	**Cluster** **Macro** **Hybrid**				
Anvari *et al.* (2014)	DSFO		PM	CDCR	**PCA**			Y
Anvari *et al.* (2015)	DSFO		PM	CDCR	PCA			Y
Pascucci *et al.* 2015 (MODIS)	DSFO		PM	Deviate Decel	**NL**		Rules	Y
Rinke *et al.* 2017 (MODIS)	DSFZ		PC**G**M	Deviate Decel	NL		Rules	Y
Pascucci *et al.* 2017 (MODIS)	DSFZ		P**C**GM	Deviate CDCR	NL	Y	Rules	Y
Schiermeyer *et al.* 2017 (MODIS)	DSFZ			Deviate CDCR	NL	**Y**		
Yuan *et al.* 2017	DS		PC					Y
Johora and Müller 2018 (GRK1931)	DSFO		PM	GT Dev Decel		Y	Rules	
Johora and Müller 2020 (GRK1931)	DSFO		PM	GT Deviate Decel		Y	Rules	

The features in Table 2 can be classified into agent properties and zone properties.

2.3.1. Agents

Because shared spaces involve multiple agents of different classes (motorists, pedestrians, cyclists), the behaviour of agents is complex and it is critical to define agent properties including their movement capabilities, perceptual abilities, and trip objectives.

Most or all shared space microscopic models integrate a social force model (Helbing and Molnár 1995) to describe short-range inter-pedestrian interactions. In general, these shared space models also integrate the car-following model GFM (Helbing and Tilch 1998) to resolve inter-vehicular interactions. These shared space models include the MixME model (Schönauer *et al.* 2012, Rudloff *et al.* 2013) and the model developed by Anvari *et al.* (2012, 2014, and 2015). The MixME project augmented the SFM with a game-theoretic approach in the form of a Stackelberg game (Schönauer *et al.* 2012) and calibrated the utility weights to choose between strategies (Rudloff *et al.* 2013). Anvari et al. (2012, 2014, 2015) augmented the SFM by determining if and when agent trajectories were going to intersect and calculating a minimum cost change to agent velocities, usually accelerating cars and decelerating pedestrians.

At least two purely pedestrian models have also incorporated longer range conflict avoidance strategies. Moussaïd *et al.* (2011) dispensed with most social forces in favour of agents seeking free paths, incorporating conflict avoidance into the driving force. Golas *et al.* (2014) implemented a long-range conflict avoidance strategy comprising multiple tactics including an optimized microscopic model which can treat multiple far away agents as a single cluster to be avoided, using the macroscopic fundamental diagram to generate a density field which repels agents; and a hybrid tactic which combines the clustering and density field approaches. These ideas are relevant to shared spaces.

Subsequent models of shared spaces: integrate trajectory deviations as an alternative to social forces (Pascucci *et al.* 2015, 2017; Rinke *et al.* 2017; Johora and Müller 2018, 2020); improve counteragent trajectory prediction with PCA (principal component analysis) (Anvari *et al.* 2014) and cubic extrapolation (Pascucci *et al.* 2015, 2017). Some support bicycles and social groups (Pascucci *et al.* 2017, Rinke *et al.* 2017).

The effects of trip objectives on agent behaviour is largely absent from microscopic shared space models, and movement and perceptual capabilities and limitations could be further improved.

2.3.2. Zones

Shared spaces are often spatially divided into zones characterised by different rules. These zones can guide agents along infrastructure (Schönauer *et al.* 2012) or attract or repel agents (Pascucci et al. 2015, 2017; Johora and Müller 2020).

Schönauer *et al.* (2012) divided zones into two classes: road sections and intersections, as do Johora and Müller (2020). Pascucci *et al.* (2015) divides zones into three types: safe zones, danger zones, and shared zones. Safe zones exert an attraction on pedestrians within them, danger zones motivate pedestrians to avoid them or to cross them faster (and more perpendicularly), and shared zones do not prioritise any agents over others.

Shared space modelling would benefit from a more careful examination of the different types of zones and rules associated with them, such as local speed limits, agent exclusion, agent priority, and preferred travel directions. In addition, zones with multiple states may be useful to compare shared spaces with non-shared streets or to construct hybrid shared spaces.

2.4. Summary

Social force models (Helbing and Molnár 1995, *etc.*) offer a flexible microscopic transport model for pedestrians and have been extended to support vehicles (Helbing and Tilch 1998, Anvari *et al.* 2012). They have been extended to integrate game-theoretic strategies (Schönauer *et al.* 2012) and models for other modes such as bicycles (Rinke *et al.* 2017, Yuan *et al.* 2017). The social force model has also previously been extended to support stationary (waiting) pedestrians (Johansson *et al.* 2015) and infrastructure guidance (Schönauer *et al.* 2012).

Phenomena that could be implemented with a waiting model include public transport stops, cafés and kiosks. More generally, a pedestrian waiting submodel could help integrate activity modelling into a shared space traffic model. Johansson *et al.* (2015) offered three models of waiting behavior (Preferred Velocity (PV), Preferred Position (PP), and Applied Preferred Position (APP)) and allowed the waiting area to have a focal point within it. Additional waiting models may be useful for some activity nodes. The waiting areas in Johansson *et al.* (2015) may have a focal point where waiting agents look, but replacing this focal point with a shape would enable the waiting model to describe a richer set of human behaviour, *e.g.* using a line segment focal shape as stop-lines within a node to model pedestrians waiting to cross at a pelican crossing or vehicles waiting while pedestrians cross the street.

The shared space models support the analysis of the movement of agents through a shared space, but do not support analysis of the *place*-centric dimensions or synergy between *movement* and *place* aspects of a shared space. Users do not only move through shared spaces as they travel between other places, but also spend time in those places, shopping, socialising, and enjoying being there. An integrated activity model building upon the work of Hoogendorn and Bovy (2004), would therefore add significant value to a shared space model.

The best approach to capture this is likely to be a microscopic model supporting multiple transport modes, longer timescales, and more complex agent motivations. The addition of integrated activity modelling to a microscopic agent-based model will yield a more realistic model, more accurate predictions, and improvements to our ability to evaluate shared space designs.

3. Proposed model structure

This paper will discuss an agent-based model based upon an augmented social force model, supporting multiple transport modes, longer timescales, and more complex agent motivations. The model will support heterogeneous agents (pedestrians and vehicles), zones which exclude some types of agents and prioritise some agents over others, nodes which agents travel between, and integrated activity modelling.

3.1. Actors

3.1.1. Agent kinematics

An agent is partially defined by its agent-type, current shape, position, and velocity. Agents may represent pedestrians, drivers, cyclists, and other types. The acceleration of these agents is determined by the agents' own preferred position and velocity, the presence of other agents, and the presence of certain inanimate objects in the scene.
Use-cases:

Pedestrians enter the scene at an origin node, and travel towards a destination node, and leave the scene. While travelling, they will need to avoid other agents, obstacles, and any zones that currently forbid them from entering and the model will support this.

Cars enter the scene at an origin node, travel towards a crosswalk and stop before it if pedestrians are currently crossing there.

3.1.2. Zones

A zone is defined by a shape and a set of high-level rules describing when (and whether) an agent of a particular type can currently pass through it. These rules may include: temporary or permanent exclusion of one or more agent-types, prioritisation of some agent-types over others, directional constraints for agents of particular types, and speed restrictions.
Use-cases:

An obstacle could be represented by a zone with a circular or polygonal shape which excludes agents of all types at all times;

A footpath could be represented by a linear zone which permanently excludes cars and which permanently prioritises pedestrians;

A roadway section could be represented by a linear zone which permanently excludes pedestrians and prioritises motor vehicles;

A zebra crossing could be represented by a linear zone which permanently prioritises pedestrians over motor vehicles;

A signalised crossing could be represented by a zone with multiple states which excludes and prioritises pedestrians and cars differently in different states.

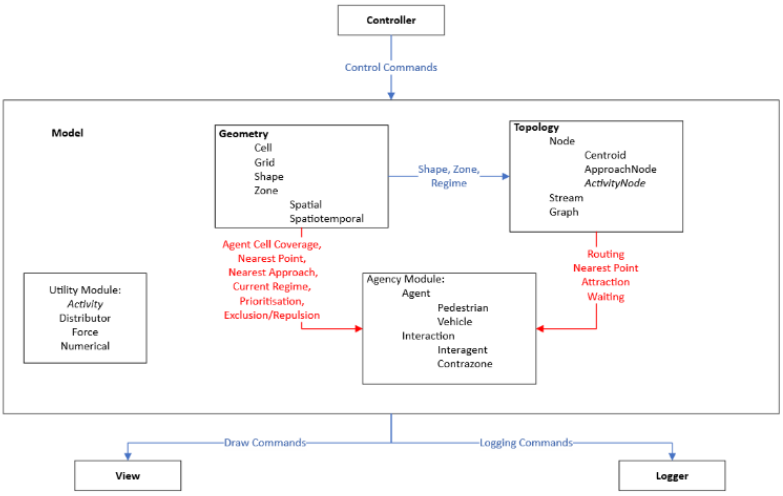


Figure 4: Software Model Design

3.1.3. Nodes

A node is defined by at least one (outer) shape and its connections (edges) to other nodes. Those edges must not pass through permanently active zones which exclude the edge's agents. Some nodes require agents to wait there before continuing towards the next node. Some nodes allow agents to perform activities there for the price of waiting there for a certain duration.

Use-cases:

A large obstacle is surrounded by nodes connected to each other but with no edges intersecting the obstacle. All agents needing to cross the obstacle must calculate a route around the obstacle rather than through it.

A multi-state exclusion-zone (*e.g.* a pelican crossing) is surrounded by approach nodes where pedestrians, cars, and other types of agents must wait their turn. At the macro-/meso-level, the route-selection algorithm used by agents may need to account for the fact that some edges will therefore have variable (and most likely stochastic) travel times. At the micro-level, the approach nodes may have another (inner) shape towards which agents will attempt to converge.

At least one café is placed near a pedestrian crossing and offers a caffeination activity to agents. The peak traffic density at or around the crossing may be affected.

3.1.4. Agency

An agent is defined not just by its kinematics, but also by the need or desire to execute particular activities. Agents may represent pedestrians, drivers, cyclists, and other types. All modelled agents need to perform the activity of travelling from an origin node to a destination node. Many (if not most) agents will need to travel through other nodes to complete this activity. Some agents will need to wait at one or more of these intermediate nodes. Some agents will want to perform activities, so will choose activity nodes where they can perform those activities, and will then travel to these activity nodes for the specific purpose of performing those activities.

Use-cases:

Pedestrians may enter the model area solely to pass though it from an origin node to a destination node.

Pedestrians may enter the model area and perform activities within the model area and then leave via the same or a different node.

Pedestrians enter the model area to pass through it, but are attracted away from their precalculated route by the opportunity to perform unplanned activities.

3.1.4. Model specification

There will be a set of agents $\boldsymbol{\alpha} \in \boldsymbol{A}$, and at all times for each agent there will be a set of active exclusion-zones $\boldsymbol{Z_\alpha(t)} \subseteq \boldsymbol{Z}$, a sequence of nodes $\boldsymbol{\nu_i} \in \boldsymbol{N_\alpha} \subseteq \boldsymbol{N}$ comprising agent $\boldsymbol{\alpha}$'s predetermined route, and a set of active waiting-nodes $\boldsymbol{W_\alpha(t)} \subseteq \boldsymbol{N_\alpha}$. Each agent will travel through the nodes along its route travelling as closely as possible to its preferred speed while constrained to avoid any active exclusion-zone $\boldsymbol{\zeta} \in \boldsymbol{Z_\alpha(t)}$ and to wait at any active waiting-node along its route $\boldsymbol{\nu} \in \boldsymbol{W_\alpha(t)}$. The most general form of the stochastic differential equation system combines agents' desires to move as they wish (most likely following a set of nodes $\boldsymbol{\nu} \in \boldsymbol{N_\alpha}$) while avoiding other agents $\boldsymbol{\beta} \in \boldsymbol{A} - \{\boldsymbol{\alpha}\}$, avoiding exclusion zones $\boldsymbol{\zeta} \in \mathbf{Z}_{\boldsymbol{\alpha}}$, and stopping at waiting nodes $\boldsymbol{\nu} \in \boldsymbol{W_\alpha} \subseteq \boldsymbol{N_\alpha}$.

If defined, an agent's optimal position should be constrained such that:

$$\boldsymbol{x}_\alpha^*(t) \notin X_\zeta \forall \zeta \in Z_\alpha(t)$$
$$d\left(\boldsymbol{x}_\alpha^*(t), \boldsymbol{x}_\beta(t + T_{\text{horizon}})\right) > r_{\alpha\beta}\ \forall \beta \in A - \{\alpha\}$$

i.e. an agent neither wants to disrespect exclusion-zones nor to collide with other agents. Note: Choosing $\boldsymbol{x}_\alpha^*(t) \in X_\nu\ \exists \nu \in N_\alpha$ should largely reproduce SFM behaviour. One could choose a "safe point" (Pascucci *et al.* 2015) to pass before, behind, or beside agent β to avoid conflict at longer range than the SFM supports.

An agent's current optimal velocity should always be constrained such that:

$0 \leq v_\alpha^*(t) \leq v_\alpha^{\max}$, $\hat{\boldsymbol{e}}_\alpha^*(t) \cdot (\boldsymbol{x}_\alpha^*(t) - \boldsymbol{x}_\alpha) \geq 0$, and $\boldsymbol{v}_\alpha^*(t) = v_\alpha^*(t)\hat{\boldsymbol{e}}_\alpha^*(t)$

Setting $\hat{\boldsymbol{e}}_\alpha^*(t) = \frac{\boldsymbol{x}_\alpha^*(t) - \boldsymbol{x}_\alpha(t)}{\|\boldsymbol{x}_\alpha^*(t) - \boldsymbol{x}_\alpha(t)\|}$, $v_\alpha^*(t) = v_\alpha^{\text{pref}} \exists v_\alpha^{\text{pref}} \in [0, v_\alpha^{\max}]$ should yield the behaviour of the classical SFM.

If $\boldsymbol{x}_\alpha^*(t) = \boldsymbol{x}_\nu \in X_\nu\ \exists \nu \in W_\alpha(t)$, then $v_\alpha^*(t) = 0$ can be used to integrate waiting behaviour into the model (Johansson *et al.* 2015).

After determining $\boldsymbol{v}_\alpha^*(t)$ and possibly $\boldsymbol{x}_\alpha^*(t)$, calculate

$$\boldsymbol{I}_\alpha = \boldsymbol{I}_\alpha^{\text{nav}}(\boldsymbol{v}_\alpha^*, \boldsymbol{v}_\alpha) + \sum_{\substack{\beta \neq \alpha \\ \beta \in A}} \boldsymbol{I}_{\alpha\beta}^{\text{IA}}\left(\boldsymbol{x}_\alpha, \boldsymbol{v}_\alpha; \boldsymbol{x}_\beta, \boldsymbol{v}_\beta\right) + \sum_{\zeta \in Z} \boldsymbol{I}_{\alpha\zeta}^{\text{CZ}}\left(\boldsymbol{x}_\alpha, \boldsymbol{v}_\alpha; \boldsymbol{x}_\zeta^*(\boldsymbol{x}_\alpha, \boldsymbol{v}_\alpha)\right)$$

$$m_\alpha \dot{\boldsymbol{v}}_\alpha = \boldsymbol{F}_\alpha = \boldsymbol{F}_\alpha^{\text{drive}}(\boldsymbol{I}_\alpha) + \sum_{\substack{\beta \neq \alpha \\ \beta \in A}} \boldsymbol{F}_{\alpha\beta} + \sum_{\zeta \in \mathrm{Z}} \boldsymbol{F}_{\alpha\zeta} + m_\alpha \boldsymbol{\xi}_\alpha$$

Equation 5: Multimodal Social Force Model

where navigational influence, inter-agent influence, and contra-zone influence are defined by:

$$\boldsymbol{I}_\alpha^{\text{nav}} = \frac{\boldsymbol{v}_\alpha^* - \boldsymbol{v}_\alpha}{T_{\text{relax}}}$$
$$\boldsymbol{I}_{\alpha\beta}^{\text{IA}} = \left(1 - w_{\alpha\beta}^{\text{CFM}}\right)\boldsymbol{I}_{\alpha\beta}^{\text{SFM}} + w_{\alpha\beta}^{\text{CFM}}\boldsymbol{I}_{\alpha\beta}^{\text{CFM}} \exists w_{\alpha\beta}^{\text{CFM}} \in [0, 1]$$

$$\boldsymbol{I}_{\alpha\zeta}^{\text{CZ}} = A_{\alpha\zeta} \exp\left[-\frac{d_{\alpha\zeta} - r_{\alpha\zeta}}{D_{\alpha\zeta}}\right] \hat{\boldsymbol{n}}_{\alpha\zeta}$$

and $\boldsymbol{I}_{\alpha\beta}^{\text{SFM}}$is defined by the social force model and $\boldsymbol{I}_{\alpha\beta}^{\text{CFM}}$ is defined by a car-following model such as the GFM or IDM. It is important to define $\mathrm{w}_{\alpha\beta}^{\text{CFM}} = w_{\alpha\beta}^{\text{CFM}}(\hat{\boldsymbol{v}}_\alpha \cdot \hat{\boldsymbol{e}}_{\alpha\beta})$ appropriately, such that $w_{\alpha\beta}^{\text{CFM}} \equiv 0$ for pedestrians and cars in different lanes, $w_{\alpha\beta}^{\text{CFM}} = 1$ for cars travelling in the same direction in the same lane, *etc*. The context in which agents operate and navigate can affect their desired current position $\boldsymbol{x}_\alpha^*$, their desired current speed v_α, desired direction $\hat{\boldsymbol{e}}_\alpha$, *etc.*

This model formally decouples an agent's desires represented by the total influence $\boldsymbol{I}_\alpha$ from the physical force $\boldsymbol{F}_\alpha$ with the sole linkage being a vector-valued function $\boldsymbol{F}_\alpha^{\text{drive}}(\boldsymbol{I}_\alpha)$ which will limit the agent's speed and direction to plausible values in the absence of external forces. Most social force models have limited the speed of agents (Helbing and Molnár 1995, *etc.*) and shared space models have limited the rate of change of agent direction for vehicles (Schönauer *et al.* 2012, Anvari *et al.* 2012) and pedestrians (Pascucci *et al.* 2015, Yuan *et al.* 2017)

Table 3: Preferred position and velocity example use-cases

Agent-State S_α	Parameter	Preferred Position $\boldsymbol{x}_\alpha^*$	Preferred Direction $\hat{\boldsymbol{e}}_\alpha$	Preferred Speed v_α^*
Approaching	Node ν	$\boldsymbol{x}_\nu \in X_\nu$	$\hat{\boldsymbol{e}}_\alpha^* = \frac{\boldsymbol{x}_\alpha^* - \boldsymbol{x}_\alpha}{\lVert \boldsymbol{x}_\alpha^* - \boldsymbol{x}_\alpha \rVert}$	$v_\alpha^* = v_\alpha^{\text{pref}}$
Converging / Waiting	Node ν	$\boldsymbol{x}_\nu \in X_\nu$		$v_\alpha^* = \frac{v_\alpha^*}{d_\nu^{focal}}$
Following	Agent β	$\boldsymbol{x}_\delta = E[\boldsymbol{x}_\beta(t)] - s_\alpha^* \hat{\boldsymbol{v}}_\beta$		$v_{\text{CFM}} \exists$CFM[1] *e.g.* GFM[2], IDM[3]
Deviating Behind	Agent β	$h = \frac{1}{2} l_{\alpha\beta} + d_{\text{safety}}^{\text{behind}}$ $\boldsymbol{x}_\delta = E[\boldsymbol{x}_\beta(t)] - h\hat{\boldsymbol{v}}_\beta$		$v_\alpha^* = v_\alpha^{\text{pref}}$
Deviating Beside	Agent β	$h = \frac{1}{2} w_{\alpha\beta} + d_{\text{safety}}^{\text{lateral}}$ $\boldsymbol{x}_\delta = E[\boldsymbol{x}_\beta(t)] \pm h\hat{\boldsymbol{v}}_\beta^\perp$		$v_\alpha^* = v_\alpha^{\text{pref}}$

Table 2 shows examples of agents in different states. Each state corresponds to an agent trying to achieve a particular goal by satisfying the defined kinematic criteria, and corresponds to previous literature: goal-directed movement (Helbing and Molnár 1995), deviating to avoid conflict (Pascucci *et al.* 2015), and waiting (Johansson *et al.* 2015). Modelling agent states and transitions between them allows a richer set of agent behaviour to be modelled.

4. Future research

The model framework must be more fully developed and validated, so that it can be qualitatively validated against common use-cases and quantitatively against data collected from real shared spaces.

5. Conclusion

The creation of shared road infrastructure is becoming increasingly important, due to the value of enhancing traffic management and the social and economic aspects of a community. To that end, the paper has considered relevant literature with an emphasis on modelling pedestrians and vehicles in the context of shared road infrastructure. This literature has included

---

[1] Car-Following Model

[2] Generalised Force Model (Helbing and Tilch 1998)

[3] Intelligent Driver Model (Treiber and Helbing 1999)

publications related to pedestrian modelling and vehicle modelling, as well as literature dedicated to shared spaces in particular.

Previous pedestrian models have supported interactions between pedestrians and other pedestrians and static obstacles. At least one model has also integrated an activity model, which would enable a shared space model to better model real human behaviour and improve its accuracy. Previous vehicle modelling literature has described methods to model interactions between vehicles and other vehicles and pedestrians at marked crossings.

Most or all shared space microscopic models integrate a social force model and a car-following model. The major differences between previous shared space models concern interactions between vehicles and pedestrians, but the conditions under which particular long-range conflict avoidance tactics and strategies are applicable to different classes of agents needs more research.

This paper describes a novel model structure to support and enhance the evaluation of shared space designs prior to implementation, and predict the effect of redesigning pre-existing shared spaces. An adapted social force model has been developed to describe and visualise shared road infrastructure, especially shared spaces with an absence of separating infrastructure between users, and to output metrics that can be used in conjunction with the latest evaluation approaches.

Acknowledgments

The authors are thankful to iMOVE for partially supporting the research (project 5-054). We would also like to thank our anonymous reviewers for their insight and constructive criticism.

References

Anvari, Bani; Daamen, Winnie; Knoop, Victor L.; Hoogendoorn, Serge P.; Bell, Michael G.H. "Shared Space Modeling Based in Social Forces and Distance Potential Field" *Pedestrian and Evacuation Dynamics* (2012):907-916

Anvari, Bani; Bell, Michael G.H.; Angeloudis, P.; Ochieng, Washington Y. "Long-range collision avoidance for shared space simulation based on social forces" *Transportation Research Procedia 2* (2014):318-326

Anvari, Bani; Bell, Michael G.H.; Sivakumar, A.; Ochieng, Washington Y. "Modelling shared space users via rule-base social force model" *Transportation Research Part C* (2015):83-103

Auckland City Council "Shared Space Guidelines" (2017)

Blue, Victor J.; Adler, Jeffrey L. "Cellular Automata Microsimulation of Bidirectional Pedestrian Flows" Transportation research record 1678, 1 (1999): 135-141

Campanella, Mario C.; Hoogendoorn, Serge P.; Daamen, Winnie. "Improving Pedestrian Micro-Simulations with Event Steps" Traffic and Granular Flow (2007): 273-280

Chen, Xu; Treiber, Martin; Kanagaraj, Venkatesan; Li, Haiying. "Social force models for pedestrian traffic - state of the art" *Transport reviews* **38**, 5 (2018): 625-653

Chraibi, Mohcine; Seyfried; Armin, Schadschneider, Andreas. "Generalized centrifugal-force model for pedestrian dynamics" *Physical review. E, Statistical, nonlinear, and soft matter physics* **82**, 4 Pt 2 (2010): 046111

Federal Highway Administration. "Accessible Shared Streets" *FHWA-HEP-17-096* (2017)

Firth, Keith. "Removing traffic engineering control - The awkward truth?" *Traffic engineering & control* **52**, 2 (2011): 73-79

Fruin, John Joseph. "DESIGNING FOR PEDESTRIANS A LEVEL OF SERVICE CONCEPT"

Golas, Abhinav; Narain, Rahul; Curtis, Sean; Lin, Ming C. “Hybrid Long-Range Collision Avoidance for Crowd Simulation” *IEEE transactions on visualization and computer graphics* **20**, 7 (2014): 1022-1034

Hamilton-Baillie, B. “Towards shared space” *Urban Design International* **13**, 2 (2008): 130-138

Hartmann, Dirk. "Adaptive pedestrian dynamics based on geodesics", *New Journal of Physics 12* (2010)

Helbing, Dirk and Molnár, Péter. “Social force model for pedestrian dynamics” *Physical Review E* (1995)

Helbing, Dirk; Tilch, Benno. “Generalized force model of traffic dynamics” *Physical Review E* **58** (1998):133-138

Helbing, Dirk; Farkas, Illés; Vicsek, Támás. “Simulating dynamical features of escape panic” *Nature* (2000):487-490

Helbing, Dirk; Qiang, Rui; Treiber, Martin. “Analytical investigation of oscillations in intersecting flows of pedestrian and vehicle traffic” *Physical Review E* **72**, 046130 (2005)

Helbing, Dirk; Johansson, Anders. “Pedestrian, Crowd, and Evacuation Dynamics” *Encyclopedia of Complexity and Systems Science* **16** (2013): 6476-6495

Hoogendoorn, Serge; Bovy, Piet. “Pedestrian route-choice and activity scheduling theory and models” *Transportation research. Part B: methodological* **38**, 2 (2004): 169-190

Johansson, Fredrik; Peterson, Anders; Tapani, Andreas. “Waiting pedestrians in the social force model” *Physica A 419* (2015):95-107

Johora, Fatema and Müller, Jörg. “Modeling Interactions of Multimodal Road Users in Shared Spaces” *21st International Conference on Intelligent Transportation Systems* (2018):3568-3574

Johora, Fatema and Müller, Jörg. “Zone-Specific Interaction Modeling of Pedestrians and Cars in Shared Spaces” *Transportation Research Procedia 47* (2020):251-258

Kesting, Arne; Treiber, Martin; Helbing, Dirk. “Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity” *Philosophical transactions of the Royal Society of London. Series A: Mathematical, physical, and engineering sciences* **368**, 1928 (2010): 4585-4605

Kneidl, A.; Hartmann, D.; Borrmann, A. “A hybrid multi-scale approach for simulation of pedestrian dynamics” *Transportation Research Part C* (2013)

Köster, Gerta; Treml, Franz; Gödel, Marion. “Avoiding numerical pitfalls in social force models” *Physical Review E* **87**, 063305 (2013): 1-13

Lakoba, Taras I.; Kaup, D. J.; Finkelstein, Neal M. “Modifications of the Helbing-Molnár-Farkas-Vicsek Social Force Model for Pedestrian Evolution” *Simulation* **81**, 5 (2005): 339-352

Moussaïd, Mehdi; Perozo, Niriaska; Garnier, Simon; Helbing, Dirk; Theraulaz, Guy. “The walking behaviour of pedestrian social groups and its impact on crowd dynamics” *PLOS One* **5**, 4 (2010): e10047-e10047

Moussaïd, Mehdi; Helbing, Dirk; Theraulaz, Guy. “How simple rules determine pedestrian behaviour and crowd disasters” *Proceedings of the National Academy of Sciences of the United States of America 108*, 17 (2011): 6884-6888

Pascucci, F.; Rinke, N.; Schiermayer, C.; Friedrich, B.; Berkhahn, V. "Modeling of shared space with multi-modal traffic using a multi-layer social force approach", *Transportation research procedia* **10** (2015):

Pascucci, F.; Rinke, N.; Schiermayer, C.; Berkhahn, V.; Friedrich, B. “A discrete choice model for solving conflict situations between pedestrians and vehicles in shared space" *Preprint, journal unknown, available online* (2017): 316-326