Integration of a multi-modal simulation module into a framework for large-scale transport systems simulation

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Abstract. In recent years, the interest in multi-modal simulation models has increased significantly. In such models, various transport modes are simulated simultaneously, including the interactions between agents using different modes. Typical fields of application are, for example, studies on evacuations, car sharing and public transport.

Commonly used models today focus either on macroscopic simulation of large-scale scenarios with hundreds of thousands or even several million entities or microscopic simulation of small world scenarios based on complex models for the underlying physics. While the first class only deals with vehicular traffic, the second one usually also deals with pedestrians and cyclists.

Obviously, there is a gap between these two areas that has to be closed by a multi-modal simulation. This paper presents the combination of both simulation approaches integrated a single simulation framework. Its capabilities are demonstrated on a real world large-scale scenario which includes also microscopic elements.

Keywords: force-based 2D pedestrian simulation, large-scale transport systems simulation, multi-modal simulation

1 Multi-modal Simulation

1.1 State of the Art

In recent years, the interest in multi-modal simulation models has increased significantly. In such models, various transport modes are simulated simultaneously, including the interactions between agents using different modes. Typical fields of application are, for example, studies on evacuations, car sharing and public transport.

Today, there are two major areas of agent-based transport simulations. On one hand, models for large-scale scenarios with hundreds of thousands or even several million entities have been developed. To keep their computational effort feasible, they are based on simplified physical representations of traffic flows as they are known from the field of dynamic traffic assignment. On the other hand, there are models with a high level of detail and a microscopic modeling of the underlying physics for small scenarios with some hundred or a few thousand agents. While the first class only deals with vehicular traffic, the second one usually also deals with pedestrians and cyclists.

Obviously, there is a gap between these two areas that has to be closed by a multi-modal simulation. Unfortunately, a model for large-scale scenarios does not provide the necessary physical accuracy which is required for a detailed pedestrian and cyclist simulation and a detailed microscopic model cannot handle several million entities. Therefore, a new approach is required which combines the best of both worlds.

1.2 Modeling Approach

This paper presents a modeling approach that closes the gap described above by implementing a flexible multi-modal simulation that is able to handle scenarios where the level of detail varies. The implementation of this framework is done in three steps.

First, a simulation framework for vehicular traffic is extended to a simple multi-modal simulation framework with a constant level of detail. Instead of estimating travel times for non-vehicular trips, routes are created based on a multi-modal network and assigned to traveling people. This extension is based on a queue model which is computationally efficient but also limited in its ability to model microscopic interactions.

Therefore, in a second step, a force-based 2D simulation module for non-vehicular trips is integrated into the framework. The agents' high-level planning (i.e. route and destination choice) is performed on a graph representing the transport system while the low level behavior (i.e. physical interaction between the participants) is simulated with a force-based model. In this force-based model, simulation entities are emitting repelling (other agents and obstacles) and attracting forces (goal locations). The force based model itself is based on existing and well established approaches.

To allow modeling different levels of detail, the simulation module has to be able to simulate different regions of the scenario with different simulation modules. An example would be a person that walks along an empty road, what can be simulated using the queue based multi-modal simulation module from step one. However, when entering a more crowded area, the person starts to interact with other people. The queue model has difficulties to deal with those situations appropriately. This is in particular true for situations with crossing pedestrian streams. To account for those interactions, people in that area can be simulated using the force-based 2D simulation module. Therefore, the possibility to dynamically switch between those two modules will be added to the simulation framework in a third step.

1.3 Application

Today, the field of application for large-scale agent-based traffic flow micro-simulations is wide spread. On one hand, such simulations create information like traffic flows and average travel times that are used traditionally in the field of transport planning and traffic management. On the other hand, those simulations produce also additional information that can be used for many interdisciplinary tasks. Due to the agent-based approach, each person in a scenario is represented as single entity. Therefore, the movement of each single person can be tracked, which is e.g. an essential requirement for evacuation scenarios and simulations.

Other fields of application for large-scale multi-modal simulations are e.g. studies that are interested in the usage of e-bikes or ride-sharing. For both of them, it is essential that also non-vehicular modes are simulated in detail.

1.4 Requirements

The proposed multi-modal simulation has to fulfill several additional requirements that result from the combination of the two different modeling approaches. Clearly, interactions between both approaches have to be included in the combined model. If, for example, pedestrians are waiting at a crosswalk, drivers have to stop and let them pass. However, this behavior is not necessary in the vehicular-only model and therefore has to be added in the multi-modal model.

Another issue is the travel time calculation for modes which are simulated using the simple model as well as the detailed 2D force-based approach. To create consistent routing results, travel times have to be estimated on a global level using information from both models.

Some further requirements result from the necessary input data which differs for the two combined models. On one hand, a vehicular model for example does not use person specific data like age or gender. A pedestrian model, on the other hand, needs this data because a person's walk speed depends on them. Another example is data representing a road network. Vehicular models typically ignore steepness information. However, a link's steepness clearly influences the speed of people using non-motorized modes. As a result, is has to be ensured that data used from either one or both models is available in the entire multi-modal simulation framework.

2 MATSim

2.1 Framework

MATSim is a framework for iterative, agent-based transport systems micro-simulations. It is currently being developed by teams at ETH Zurich and TU Berlin as well as senozon AG, a spin-off company founded by former members of both institutes. [1] gives a detailed description of the framework, its capabilities and its structure. Because of its agent-based approach, every person in the system is modeled as an individual agent in the simulated scenario. Each agent has personalized parameters such as age, sex, available transport modes and scheduled activities. MATSim's application to a large-scale Switzerland scenario (over 6 million agents simulated on a high resolution network with 1 million links) is presented by [9].

Figure 1 shows the structure of a typical, iterative MATSim simulation run. After creation of initial demand, plans of the agents are modified and optimized in an iterative process until a relaxed system state (typically a user equilibrium) is found. The results can be analyzed later. The loop shown in the figure contains

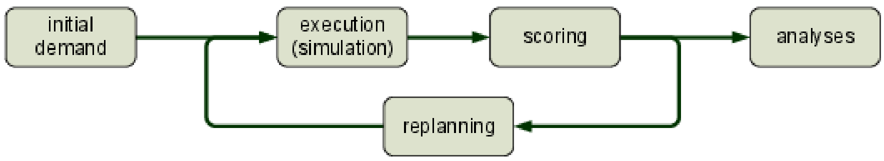


Fig. 1. Structure of the iterative MATSim loop

execution (simulation), *scoring* and *replanning* elements. Within the simulation module, agents' plans are executed. Afterward, the scoring module uses a utility function to calculate the executed plans' quality. [2] describe the basic utility function for MATSim. Based on scoring module results, the replanning module creates new plans by varying start times and durations of activities, as well as routes and modes used to travel from one activity to another.

Simulation of traffic behavior is also part of the iterative loop. The simulation module's task is to execute agents' plans within the simulated scenario. The so-called *QSim* is a deterministic, Java based implementation of a queue model using a time step based approach with a one-second step size. Within each time step, the state of the queues is considered.

By default, only car traffic is simulated physically. The travel times for other modes like walk, bike or public transport are estimated based on crow fly—or direct—distance. Support for public transport has been added recently [14].

2.2 Multi-modal Extension

In a first step, a multi-modal simulation framework with a constant level of detail is developed and integrated into the MATSim framework. Figure 2 shows the basic concept of the implementation. A multi-modal extension is added to each link object in the mobility simulation. While traffic flow dynamics are simulated by MATSim's mobility simulation using a queue model, they are not taken into account in the multi-modal extension. Having a look at typical pedestrian and cyclist traffic flows shows that congestion is very rare compared to vehicular traffic and therefore justifies the application of this simplistic approach in large parts of a scenario. For regions with higher traffic flows, this simple model is replaced with a 2D force-based model, which provides a very high level of detail, including consideration of traffic flows, by cost of additional computational effort. Besides more computational power, the 2D force-based model requires also additional information about a road's geometry.

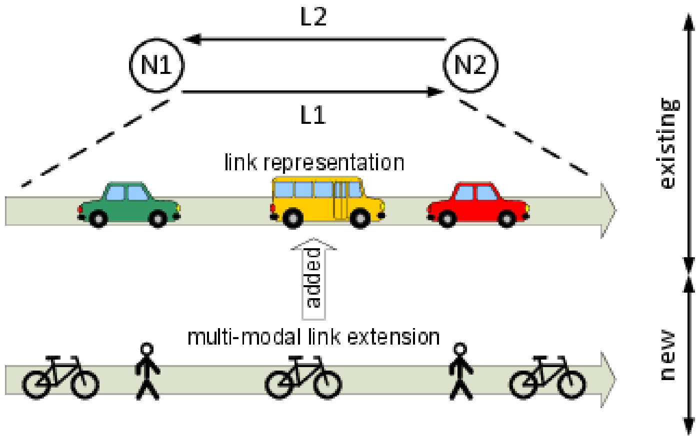


Fig. 2. Multi-modal link extension

So far, the switch between those two approach is performed semi-automatically. For each link, the multi-modal simulation type has to be specified (simple vs. detailed). Transport modes in agents' plans are not affected by this—i.e. there is e.g. only one kind of *walk* mode. A link's multi-modal extension then selects the corresponding model to simulate an agent traveling along that link. As part of future work, the specification of a link's simulation model will be fully automatized. To do so, the simulation has to monitor the traffic flows on multi-modal links. If a critical level, where congestion is expected, is exceeded on a link, traffic flows on that link have to be simulated using the 2D force-based approach. When the flows drop back below the critical level, the simulation module can be switched back to the simple approach.

In the simple model, agents traveling on a link are stored in a priority queue which orders the agents based on their scheduled link leave time (see Figure 3). This time is calculated when an agent enters a link based on parameters like the agent's age and gender as well as the links steepness. In each time step it is checked, whether the queue contains agents who have reached their link leave time and therefore have to be moved to their route's next link. An agent's position on a link is not determined by the model. However, under the assumption that agents move with constant speed, their position can be interpolated. On one hand, this approach is computationally very efficient because computation effort is only created when an agent enters or leaves a link but not during the agent is traveling along a link. On the other hand, agents can travel with different speeds and therefore overtake each other.

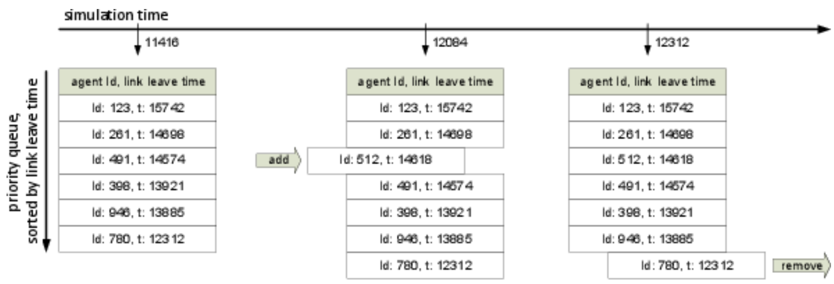


Fig. 3. Link representation in the simple model.
At time 12084, agent 512 enters the link and is—based on its calculated link leave time 14618—inserted into the queue. At time 12312, agent 780 has reached its leave time and therefore is removed from the queue.

2.3 Force-based 2D Simulation

This sections gives a brief overview of the force based agent movement model. For a detailed discussion see [**?**]. We distinguish between two stages in the movement model. The first stage deals with the low level movement of the agents, meaning collision avoidance, velocity adaptation and so on. The second stage deals with the more high level movement of the agents, meaning moving along a given route. Both stages are modeled based on additive attracting and repelling forces, which are "pushing" the agents through the environment. The general force model is defined according to Newton's law ($F = \mathrm{m} \cdot \mathrm{a}$).

$$\mathrm{m}_i \cdot \mathbf{a}_i(t) = \frac{\mathrm{m}}{\tau}\left(\mathbf{v}_i^0(t) - \mathbf{v}_i(t)\right) + \sum_{j \neq i} \mathbf{f}_{i,j}(t), \tag{1}$$

with $\mathbf{v}_i^0$ is the desired velocity vector for agent i at time t. The term $\mathbf{v}_i(t)$ denotes the agent's actual velocity at time t. The time constant τ describes the time that is needed to adjust the actual velocity to the desired velocity. The second term of the equation builds the sum over all influential entities j in the environment (i.e. other agents, walls, and obstacles). Each of those entities emit a repelling (or attracting) force to agent i.

Many different force models have been discussed in recent years (see, e.g. [10] for an overview), most of them are build on the so called social force model introduced by [7]. The basic social force model implicitly reproduces collision avoiding behavior as it can be observed in real-world situations. It has been shown that the model works particularly well in high density conditions, such as one can observe in evacuation situations [6]. In this work we adapted an extension to the social force model where collisions are explicitly avoided to the current context. Collisions are avoided by explicitly predicting potential collision points [16].

In the model each agent i computes for each other agent j in the environment the angle $\theta_{i,j}$ between $\mathbf{d}_{i,j}$ and $\mathbf{v}_{i,j}$. Where $\mathbf{d}_{i,j}$ denotes the vector pointing from agent i's position to agent j's position and $\mathbf{v}_{i,j}$ denotes the relative velocity between both agents. If $|\theta_{i,j}| > \pi/4$ then the time $t_{i,j} = \infty$. Otherwise $t_{i,j}$ reflects the time of closest approach which is the time when the distance of both agents is minimal by assuming that neither agent i nor agent j changes her velocity or direction of movement. The agent than takes the minimum of these times $t_i = \min_j(t_{i,j})$. Afterwards the agent computes the configuration of the environment for t_i by again assuming that none of the pedestrians changes her velocity or direction of movement. Let $\mathbf{d}'_{i,j}(t_i)$ denote the predicted vector pointing form agent i to agent j at time t_i. The agent j's influence on agent i (second term in Equation 1) is

$$\mathbf{f}_{i,j}(t) = \mathtt{A}_{env}\frac{v_i(t)}{t_i}\mathtt{e}^{-\mathrm{d}_{i,j}(t)/\mathtt{B}_{env}}\frac{\mathbf{d}'_{i,j}(t_i)}{d'_{i,j}(t_i)}. \quad (2)$$

The constants $\mathtt{A}_{env}$ and $\mathtt{B}_{env}$ are free parameters in the model. Equation 2 is not only applicable for other agents in the environment but also for any none moving object like walls or obstacles. The collision avoiding model describes how the environment influences the agents' movement. However, in order to move through the environment along a given route a "driving force", like the velocity adaption term in Equation 1, is needed.

In the current setup every agents start at a link in the navigation graph. A simple approach would be to let $\mathbf{v}_i^0$ point towards the to-node of the start link at the beginning. As soon as the node is reach $\mathbf{v}_i^0$ points to the to-node of the next link and so on until the agent reaches her destination. However, in [5] it has been shown that such an approach leads to an unrealistic behavior in situations when agents are moving next to each other. The reason is that those agents are pulled together at close range to a node and after the node is passed their trajectories diverge again. The authors proposed a force system that follows the route in the navigation graph. The basic idea is that each agent keeps a shadow tag on the navigation graph, which moves along the graph as the agents move forward. Furthermore, the agents are connected by a virtual rubber strap to their corresponding shadow tag. The agents are driven by a driving force that works parallel to the link which has the shadow tag on it. The virtual rubber strap pulls the agents towards the shadow tag if they diverge to far from the link. This leads to the following force:

$$\frac{\mathrm{m}_i}{\tau}\left(\mathbf{v}_i^0(t) - \mathbf{v}_i(t)\right) + \mathtt{A}_{path}\mathtt{e}^{d_i^p(t)/\mathtt{B}_{path}}\mathbf{d}_i^p(t), \quad (3)$$

where $d_i^p(t)$ is the agent i's distance to the current link, and $\mathbf{d}_i^p(t)$ is the perpendicular unit vector pointing from the agent to the current link.

Sticking all together the agents' acceleration at time t is given by:

$$\mathbf{a}_i(t) = \frac{1}{\tau}\left(\mathbf{v}_i^0(t) - \mathbf{v}_i(t)\right) + \frac{1}{\mathrm{m}_i}\left(\mathtt{A}_{path}\mathrm{e}^{d_i^p(t)/\mathtt{B}_{path}}\mathbf{d}_i^p(t)\sum_{j\neq i}\mathtt{A}_{env}\frac{v_i(t)}{t_i}\mathrm{e}^{-\mathrm{d}_{i,j}(t)/\mathtt{B}_{env}}\frac{\mathbf{d}'_{i,j}(t_i)}{d'_{i,j}(t_i)}\right) \quad (4)$$

This leads to a model with four free parameters ($\mathtt{A}_{env}$, $\mathtt{B}_{env}$, $\mathtt{A}_{path}$, and $\mathtt{B}_{path}$).

In the rubber strap analogy discussed above the agent would switch to the next link as soon as the shadow tag moves over the node. This means, at the end of each link is virtual perpendicular finish line and as soon as the agent crosses that finish line, the shadow tag is assigned to the next link. However, as it is pointed out in [4], this approach results in an artifact if the angle between two consecutive links is smaller than $\pi/2$. In those cases the agents will move toward the inner curve of the path, which is not plausible. The proposed solution that is implemented her is that the finish line is not perpendicular to the link but it corresponds to the bisector of the angle between both links.

The model for the agent movement defined in Equation 4 defines the agents' acceleration in a continues time model. However, in order to integrate the model into a computer simulation the time has to be discretized. This means an agent's velocity will only be updated at discrete time steps. There are different ways how to update velocities at discrete time steps. A common used way is the Euler-Cromer method (see, e.g. [3]), which ends up in the following equations:

$$\mathbf{v}_i(t+h) = \mathbf{v}_i(t) + h\mathbf{a}_i(t) \quad (5)$$

$$\mathbf{r}_i(t+h) = \mathbf{r}_i(t) + h\mathbf{v}_i(t+h) \quad (6)$$

Where $\mathbf{r}_i(t)$ is the agent i's position at time t and h is the time step size.

2.4 Multi-modal Travel Times

Travel time calculation for motorized modes is already implemented in MATSim. Therefore, this section focusses on travel time calculation for non-motorized modes.

Walk travel time calculation is based on results of a comprehensive literature review presented by [15]. Starting point is a normal distributed reference speed of 1.34 m/s with a standard deviation of 0.26 m/s, which leads to an individual reference speed for each person. Using this value and respecting a person's age and gender, a personalized speed is calculated (see Figure 4(a)). Finally, to calculate the person's travel time on a specific link, the influence of the link's steepness on the person's speed is taken into account (see Figure 4(b)). The combination of person specific attributes and link steepness is shown in Figures 4(c) and 4(d). As a result, a person's speed on plain terrain is calculated like:

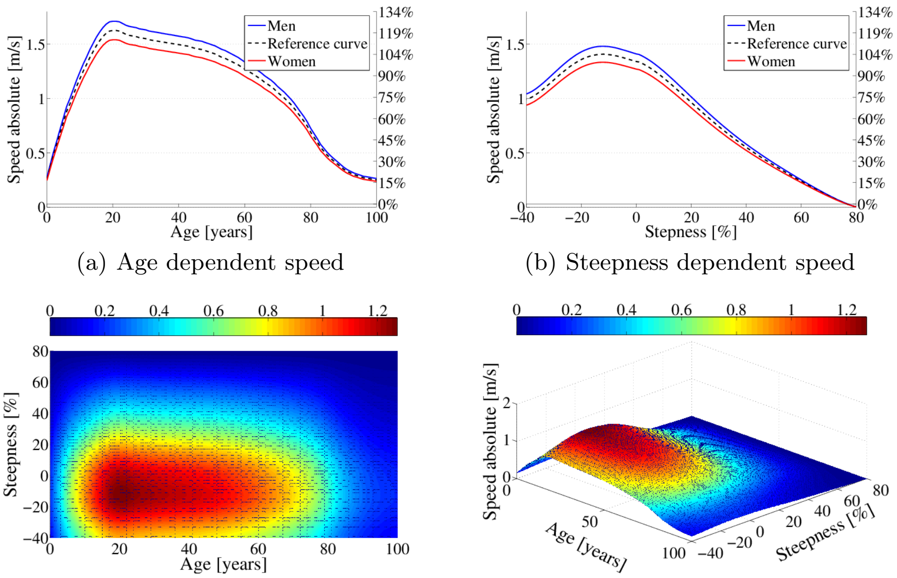
$$\textit{person scale factor} = \textit{statistical spreading factor} \cdot \textit{gender factor} \cdot \textit{age factor} \quad (7)$$

$$v_{person,walk} = v_{reference,walk} \cdot \textit{person scale factor} \quad (8)$$

A link's steepness is respected like:

$$v_{person\ walks\ on\ link} = v_{person,walk} \cdot steepness\ factor \qquad (9)$$

The speed of cyclists is determined using results from [11]. Starting point is



(a) Age dependent speed (b) Steepness dependent speed

(c) Age and steepness dependent speed (d) Age and steepness dependent speed (3d)

Fig. 4. Speed of pedestrians

again an individual person speed based on a normal distributed ($\mathcal{N}(6.01, 1.17^2)$) reference speed. Again, a person's speed is calculated by respecting age and gender attributes (see Figure 5(a)).

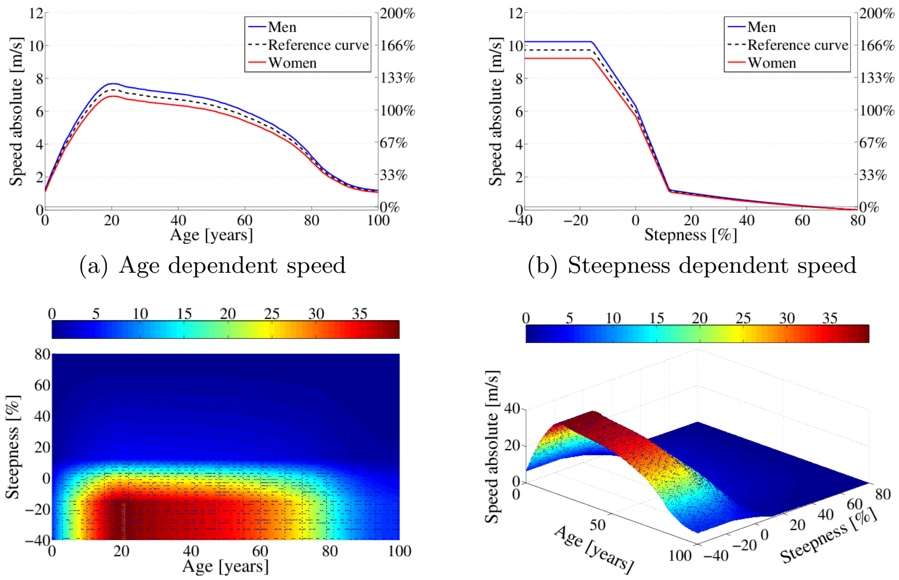
When calculating the steepness factor, it is distinguished whether a links goes uphill or downhill. When going uphill, the person's speed is reduced by a factor which is calculated based on the grade and a reference factor of 0.4002 m/s which is scaled by the same factor as the person's reference speed. I.e. the speed drop of slow people is lower than the drop of fast people. When the bike speed drops below the walk speed, which happens at a grade of approximately 12%, it is assumed that the person's switches to walking (see Equation 11). For downhill links a reference factor of 0.2379 m/s is used. Additionally it is assumed, that cyclists limit their speed to 35 km/h (9.7222 m/s; see Equation 12).

$$v_{person,bike} = v_{reference,bike} \cdot person\ scale\ factor \tag{10}$$

$$v_{person,uphill} = max \begin{cases} v_{person,bike,flat} - 0.4002 \cdot |grade| \cdot person\ scale\ factor \\ v_{person,walk,uphill} \end{cases} \tag{11}$$

$$v_{person,downhill} = min \begin{cases} v_{person,bike,flat} + 0.2379 \cdot |grade| \cdot person\ scale\ factor \\ 9.7222 \end{cases} \tag{12}$$

Another parameter that affects the speed of pedestrians and cyclists is the



(a) Age dependent speed (b) Steepness dependent speed

(c) Age and steepness dependent speed (d) Age and steepness dependent speed (3d)

Fig. 5. Speed of cyclists

crowdedness of the link where they are physically present. Data to take this effect into account is again presented by [15]. However, to calculate the crowdedness of a link, its geometry has to be taken into account. One method of doing this is discussed in [8]. In the following we give a short description of this method. we assume that the geometry of a link is represented by a simple polygon. Important parameters of the polygon are:

- Link area A
- Link minimum width w

While the area of a polygon is straightforward to calculate, there is no obvious approach to calculate the minimum width of the link. One way is first to calculate the median, which can be derived from the medial axis of a polygon (see, e.g. [13] for a "medial axis" algorithm), and afterwards calculating the minimum border to border distance orthogonal to the median. Having this parameters we can calculate the storage capacity and flow capacity of the link. The storage capacity for pedestrians usually is given in persons per area. In Weidmann's work a pedestrian flow comes to a stand still at a density of $\rho^{max} = 5.4\,/m^2$. This means, the storage capacity of a link is $A * \rho^{max}$. The minimum width of the link defines the bottleneck and so the part with the smallest flow capacity of the link. This leads to the following definition of the flow capacity:

$$q = w * 1.33 \frac{1}{m * s}. \tag{13}$$

This means, a bottleneck with a width of one meter has a flow capacity of $1.33\,/s$, which reflects a generally accepted value (see, e.g., [12]).

3 Scenario

The capabilities of the introduced multi-modal simulation framework are demonstrated on the model of a shopping center which is located near the main station in the city of Zurich (see Figure 6) and can be reached either by walking, cycling, public transport (SBB) or car. People walking or using public transport have

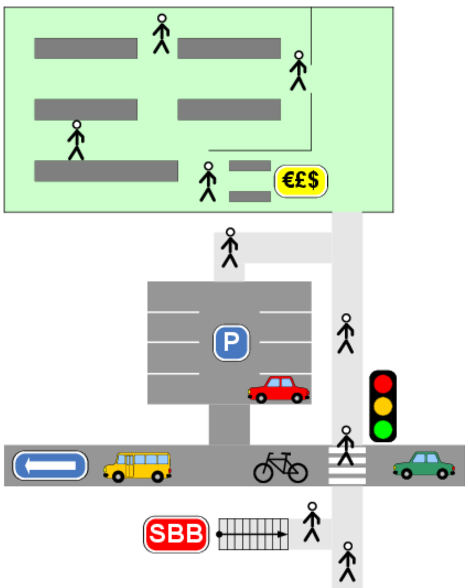
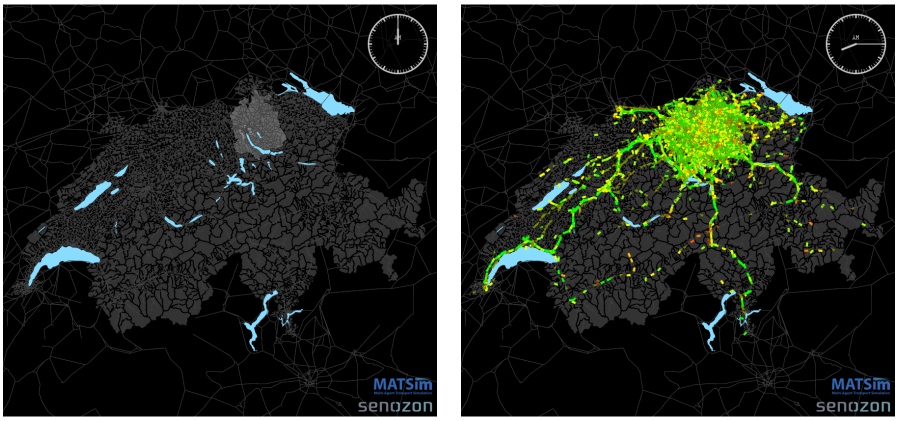


Fig. 6. Shopping center

to cross a road at a signalized crosswalk. The shopping center is embedded into a scenario of the Canton Zurich which contains 450,000 agents—a 25% sample of the entire population—that are simulated on a planning network with 24,000 nodes and 60,000 links. Figure 7(a) shows a map of Switzerland containing the road network and the study area (colored light grey). The population consists of all people, that touch the study area during one of their activities or trips. Therefore—as shown in Figure 7(b)—not only the canton's residents but also people who cross the canton, are included. Figures 8 and 9 give a more de-



(a) Switzerland without traffic flows (b) Switzerland with traffic flows at 08:15 a.m.

Fig. 7. Switzerland

tailed look of the study area. Vehicles are drawn as rectangulars, pedestrians and cyclists as arrows. Pedestrians simulated using the force-based approach are represented by circles. The color of a vehicle/person represents its velocity relative to its maximum allowed speed (red: min, green: max). Finally, the full capability of the multi-modal simulation becomes visible when having a look at the shopping center (see Figures 10 and 11). Marker A shows the traffic lights at the intersection. A pedestrian (B) crosses the street while a vehicle (C) has to wait until its light signal becomes green. Marker D points to an agent which has just parked its car and is now walking to the shopping center. A vehicle leaving its parking lot is shown by marker E. Two agents inside the shopping center are shown by marker F. One walking along the floor (walking at normal speed, therefore colored green), another one picking up an article from a shelf (stopped, therefore colored red). The switch between the simulation modes is performed when agents reach the points marked with G (for walking agents) respectively when they leave/enter their car on the shopping center's parking area.

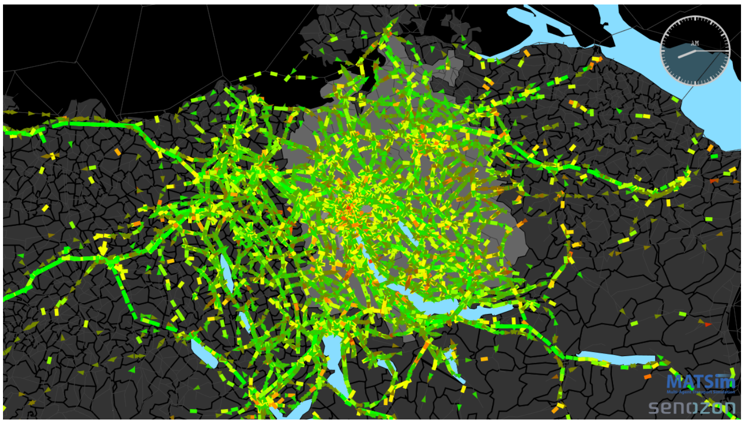


Fig. 8. Canton Zurich with traffic flows at 08:15 a.m.

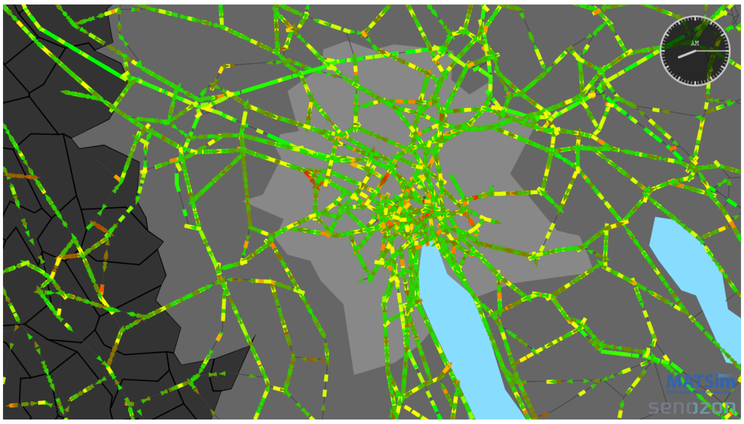


Fig. 9. City of Zurich with traffic flows at 08:15 a.m.

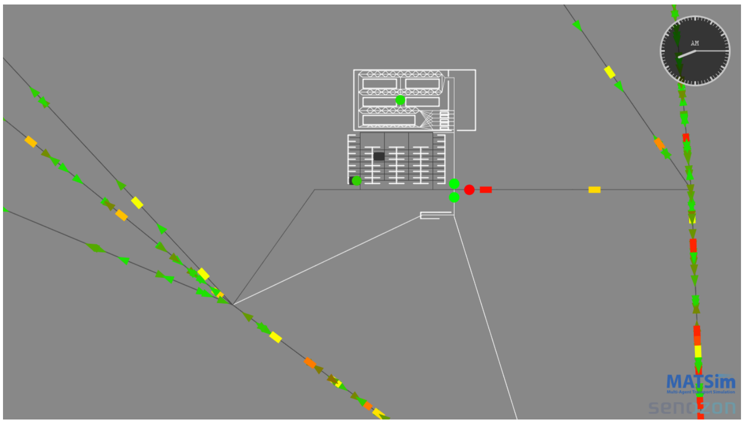


Fig. 10. Shopping center with traffic flows at 08:15 a.m.

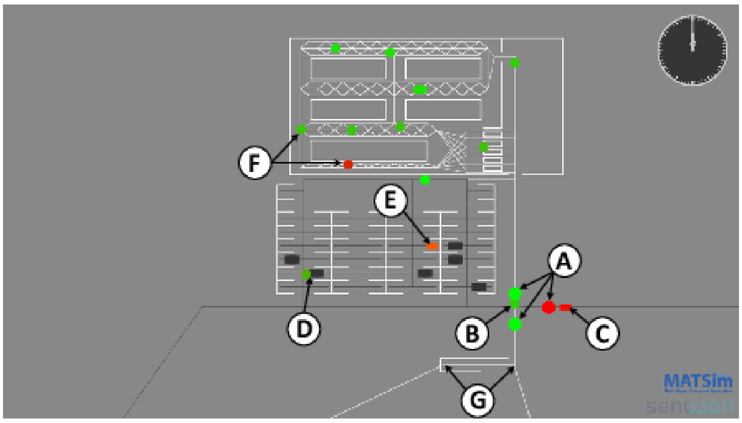


Fig. 11. Shopping center with traffic flows at 12:00 p.m.

4 Conclusions

We explained why there is a growing interest in microscopic large-scale multi-modal simulations. Existing models are limited by available computation power and therefore are either large-scaled or microscopic. Since the required level of detail varies in large scenarios, we propose an approach where the level of detail is also flexible. This allows combining a framework for large-scale simulation with a microscopic force-based 2D simulation.

Depending on an agent's position and its transport mode, it is simulated either with a faster or more details simulation approach. However, so far interactions between agents simulated with different approaches are not included in the framework. As a result, agents walking from their parking lot to the shopping center do not force cars to slow down. Therefore, the next step of development will be adding the capability to take such interaction into account to the framework.

So far, the user has to statically define the level of detail for each part of the scenario. This process will be automatized in a two step approach. First, the possibility to dynamically switch a region's level of detail during the simulated time period will be added. As a result, the shopping center from this paper's scenario could be simulated using the force-based approach only during opening hours. In a second step, the simulation will take control over the dynamic level of detail adaption using real time data like crowdedness. As a result, the simulation will switch a link's simulation mode to the force-based model when it is too crowded and vice versa.

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