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A HOLISTIC GUIDING SYSTEM FOR PEDESTRIANS: PROOF OF CONCEPT

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Abstract. Crowds could be made safer and flow more efficient by guiding pedestrians through an automatic system. Yet, no such system is being employed anywhere in the world. In former work we tackled obstacles to this goal: sensing and distributing of congestion information through a direct communication network, resolving congestion through directional instructions when facing limited compliance, and collecting data on compliance behavior through an online survey. Here, we combine all into one socio-technical system that we realize as a computer model. We demonstrate through simulation experiments how congestion at metro station Münchner Freiheit is resolved.

Keywords: Socio-technical system, control loop, guiding strategies, compliance, adherence, pedestrian modeling, direct mobile communication, survey.

1. Introduction

Whether at large events or in everyday pedestrian traffic, crowds could be made safer and flow more efficient if one succeeded in guiding pedestrians towards better routes, as one does with cars. Ideally this would happen through an automatic system without involving human crowd managers: The system could measure crowd densities. An app could make information available to anyone with a smartphone and issue instructions. People would react to the instruction which, in turn, would affect the pedestrian flow. A control systems emerge as illustrated in Figure 1.

The idea of crowd sensing systems based on apps goes back more than a decade. For example, [1] devise smartphone-based technology to sense crowd densities. Their app offers a number of tabs with potential information, but no personal directional instructions that people could comply with or ignore. Thus, the system gives a situational overview and triggers individual reactions but it does not constitute a system control loop. A few years later, the authors in [2] envision an overall guiding system including instructions, but restrict their research to the technical side: They build a positioning sensing system that also gives route instructions in their laboratory. They investigate it through controlled experiments with consenting students. The students carry prototypes. Compliance within this kind of study is necessarily 100 %.

The system proposed in this work constitutes a complete socio-technical control loop: crowd density is sensed, route instructions are derived, pedestrians may adhere or not, and their collective behavior feeds back into the crowd state. This fundamentally differs from most existing approaches, which either provide descriptive congestion information only or consider system-level control strategies that assume fully compliant, fluid-like pedestrians [7, 8]. From a system-theoretical perspective, these approaches are based on feedback loops operating on different levels. Pedestrians form individual feedback control systems, while a technical guidance system introduces an additional feedback loop at the system level [9], see Figure 2.

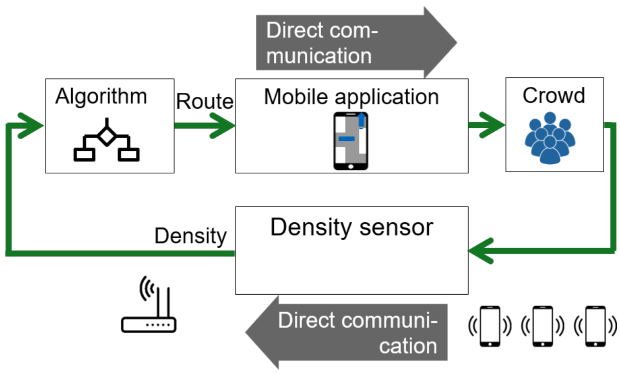

Figure 1. Components of a crowd guidance system that have been already analyzed in Ref. [3–6]: information gathering and transmission, a robust guiding algorithm capable of handling low compliance, and mechanisms to foster compliance. The focus of this study is on the complete system. We integrate components into an overall concept and test it, through computer simulations, for a real life use case.

Existing work typically considers only one of these loops in isolation. The integrated modeling and evaluation of interacting individual- and system-level feedback loops is a central contribution of this work. Our following description of the state-of-the-art, therefore, focuses on crowd density based control systems.

In addition, we rely on novel direct communication technology among pedestrians' smart phones to both sense crowd densities on routes and to transmit information. It uses sidelink communication which

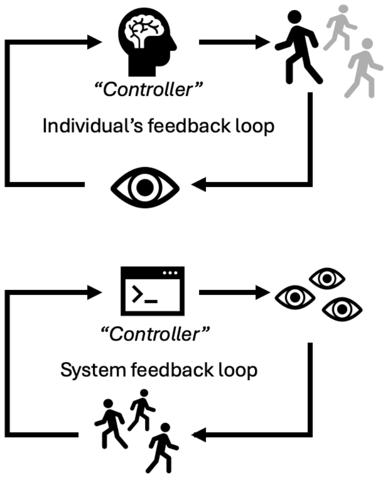

Figure 2. Feedback loops at two levels in a socio-technical system. The human in its environment responds to information (top). There may be a technical component that generates information based on the system's state (bottom). The proposed system (Figure 1) comprises both levels.

has been standardized only very recently [10]. Our crowd sensing algorithm fully anonymizes all position data and thus ensures complete personal privacy [11]. This is an advantage over concepts like [1] for which the active consent of all participants is needed which constrains applications in public spaces.

While the communication technology has not yet been fully rolled out, simulation studies, that are typical in the development phase of mobile systems, provide evidence that the proposal is technically feasible (see Ref. [3, 6, 11–14]). A centrally installed algorithm assesses the density information and computes route suggestions which are displayed on the mobile devices so that people can react [4, 5]. The density information itself is transmitted and aggregated in a decentralized way [11].

Yet, while the idea may seem obvious and has been put forward before [2], as of today no such system is being employed anywhere in the world. A number of factors make the task more challenging than for car traffic where we have a range of guidance systems, not just Google Maps, in everyday use. On the technical side, we need a way to sense congestion in crowds that are often distributed over an area that may be hard to survey, even by cameras. Also, instructions need to be distributed within the crowd. Direct mobile communication based on sidelink was suggested as solution to both issues in former work [3, 6, 11–14].

However, most issues are non-technical. In particular, pedestrians need to perceive and understand instructions. This makes good message design a crucial prerequisite and integral part of the system. We argue that it cannot be left to unspecified devices. For example, [15] and [16] assume that there is an abstract guiding signal that can be adjusted at will and that attracts people like a force to an exit. This, in our eyes, translates to ideal compliance.

Further, people must be able to comply with the instructions. Since people do not monitor their walking speeds, adjusting one's walking speed to a specified value seems out of the question. Telling people to speed-up or slow down, seems just as impractical when we have elderly, people with luggage or families with small children in a crowd. In view of this, building a full control system on speed adjustments, as for example in [17], appears over-optimistic.

We would also like to point out that information must be identical for all members of a group traveling together. Groups will not conveniently split up and distribute over different routes to accommodate the needs of an algorithm. Instead confusion will likely worsen congestion.

Most importantly, unlike water molecules, people need to be convinced to comply. Even under the best of circumstances, compliance will be nowhere near 100 % as often assumed in former concepts of control systems for pedestrian traffic.

Therefore, we argue that the goal must be to devise a crowd guidance algorithm that works even for low compliance. We believe that in a case like that, simpler is better. In Ref. [4] we presented such a procedure based on density measurements and route directions.

Finally, message design to foster people's adherence to instructions is a true inter-disciplinary task. Fortunately, when messages are tailored to a specific scenario and target group, adherence levels that suffice to alleviate congestion can be achieved [5].

In summary, there are solutions to all three subproblems: technical functionality of density sensing and message transfer, devising a guidance algorithm to deal with low compliance and achieving a level of adherence to instructions that allows the algorithm to perform.

However, considering these components in isolation is insufficient, as they interact. To assess whether an overall system is effective, it must be conceptualized and tested as an integrated whole, for a realistic scenario and for a realistic number of pedestrians. We will do this in this contribution.

2. Methods: System components and simulation tools

2.1. System components

The system's major components are the mobile network, the algorithm and the crowd shown in Figure 1.

To sense congestion, we rely on direct communication technology among pedestrians. Each mobile phone acts as a sensor and, at the same time, as a hub in a transmission network. Local information on pedestrian positions, based on GPX, is aggregated into a density map through information exchange among participants. Maps are fully anonymized. We refer to Ref. [6, 11, 13, 14] for the technical description and feasibility tests from a telecommunication perspective. Crucially, information transmission through this moving network is sufficiently fast for people to react in time to cues [3].

In Ref. [4] we proposed a very simple guidance algorithm based on independent density measurements. We gave route instructions towards the least used route when congestion was detected. Also, we issued the same instruction to all recipients to avoid confusion. We demonstrated, for an abstracted scenario, that compliance as low as 30 percent may suffice to resolve congestion.

In an online survey with almost 1 000 soccer fans, and a control group of about 500 faculty and staff at Hochschule München, we compiled realistic compliance distributions with respect to app designs that conveyed directional suggestions. We presented participants with app designs that differed in amount and quality of information. The base design showed an arrow pointing to the suggested route. In other designs we added and combined information on the congestion state en route and an appeal to the team spirit of the soccer fans. We saw that, when congestion information was added, compliance with route suggestions among soccer fans sufficed to significantly reduce jams in an abstracted scenario very similar to the one in this contribution (see Ref. [5]).

2.2. Simulation tools

We simulate signal transmission, that is the physics and the handling of protocol stacks in the network, with *OMNeT++* [18], and human locomotion with the optimal steps model in *Vadere* [19]. Both simulation frameworks are free and open-source. They are complemented by *flowcontrol*, a new Python framework to simulate the functionality of crowd guidance algorithms while varying compliance [20]. All three become modules in the new *CrowNet* simulation framework through which we run the simulations of the overall system. *CrowNet* is described partly in [20] and in a dedicated publication [12].

3. Results: Simulation of an integrated crowd guidance system

All three aspects–information gathering and transmission, a robust guidance algorithm capable of handling low compliance, and mechanisms to foster compliance – are essential building blocks of a functional system. But will it work for real people in a real world scenario, when all components interact? A related question is whether the system can be scaled to the size of a real-world scenario, realistic crowds, and the resulting telecommunications traffic load. To answer these questions, we compose an overall concept. We realize this complex socio-technical system as a computer model and evaluate it through simulation experiments.

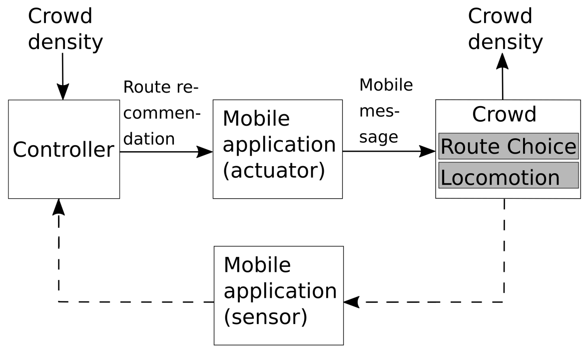

Figure 3. The *CrowNet* framework allows to simulate crowd guidance based on direct communication. The crowd guidance system is represented as a control loop where the algorithm, implemented in the controller, generates route recommendations. The recommendation is disseminated through a mobile application based on direct communication (actuator). The algorithm uses density measurements provided by another mobile application (sensor) as input.

A classic control loop in the *CrowNet* framework represents the crowd guidance system. It is visualized in Figure 3. The controller receives information on the level of service and the comfort level, coded through the crowd density on each route from the decentralized density map. The density map is computed on every smart phone, which leads to as many maps as there are individuals. The maps need not be identical [6, 11]. They are aggregated at the relay station. The controller contains the guidance algorithm that computes route recommendations. These are disseminated to the crowd through another mobile application. In [5] we suggested suitable app designs for this purpose. People can react to the recommendations by altering their route, that is, walk a different path.

The goal is to significantly decrease the density in the most crowded area, which is the shortest and preferred route to the trains at a metro station. The success depends on every single part of the system.

Figure 4 is a snapshot of the layout of the simulation in *Vadere's* graphical user interface. Our test scenario mimics the hours before a Bayern München soccer match. Fans alight from busses and trams at metro station Münchner Freiheit to board trains to the soccer arena. Please refer to [20] for the simulation parameters that lead to a typical influx to the area. The arrival area is marked with a bus symbol. There are three routes to an intermediate level from which the train platforms can be accessed. Agents choosing the shortest and preferred path in Figure 4 leave an orange trajectory. Trajectories on the two longer paths are blue. The relay station is positioned slightly north to the bus and tram stop. The topography in the simulation is realistic, with twists and turns and varying corridor widths that correspond to measurements taken at the metro station.

Figure 5 zooms in on the shortest route. The measurement area on the shortest route is highlighed in

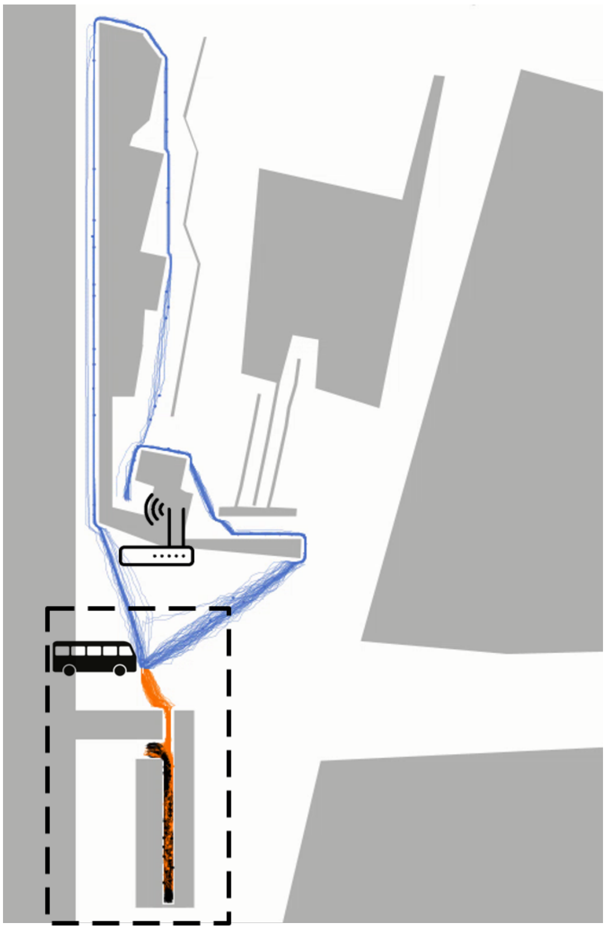

Figure 4. Bird's eye view of the simulation layout. The area where busses and tram arrive is marked with a bus. Gray areas are obstacles, like walls but also shops. Agents choosing the shortest route leave orange trajectories, agents on the longer paths leave blue trajectories. There is counterflow on the short route with black trajectories. The relay symbol marks the location of the controller where the guidance algorithm runs.

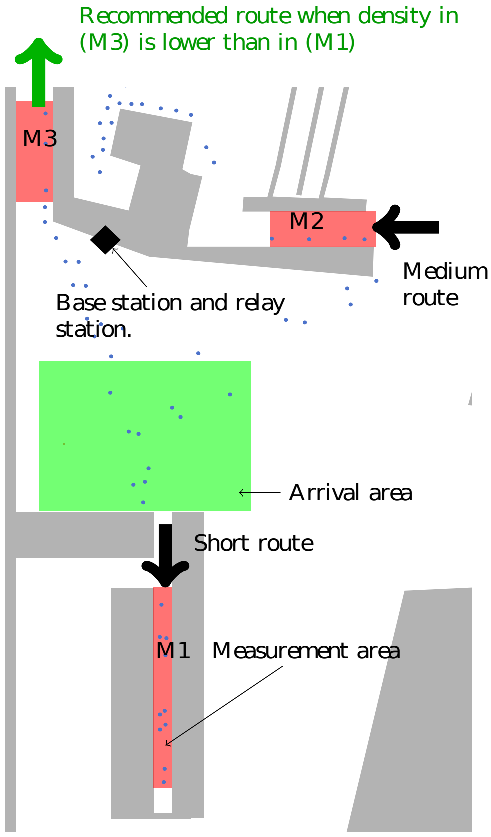

Figure 5. Guidance system with controller station: Topography model in the *Vadere* GUI. Obstacles are displayed in grey, measurement areas in red (M1, M2, M3), the arrival area in green . Football fans (small dots) exit the bus or tram in the arrival area where an app provides route recommendations. The route recommendation algorithm, implemented in the controller station, compares the densities along the short (M1) and the long route (M3) every 2s. The long route is recommended if and only if the density in (M1) is higher than in (M3). Figure adapted from Mayr [20].

red and marked M1. The measurement areas on the longer routes are located at the beginnings of the routes and are marked M2 and M3. The arrival area is highlighted in green.

The left of Figure 6 visualizes the resolution of the density map, that is, the cells for which density values are estimated. Each cell has size $1\,\mathrm{m} \times 1\,\mathrm{m}$. The right of Figure 6 explains how agents relay their individual density maps, that is their estimates for pedestrians per cell to the relay station (marked with a black diamond). The agents' communication channels to the relay station are shown as black lines marked with an R. All agents–blue dots–also interchange density information directly to inform their individual density estimates. They would do this even if they had no connection to the relay station. Information exchange links between agents are shown as red lines marked with a D in the schematic of Figure 6. Density information and route recommendations are disseminated in separate mobile apps using LTE sidelink communication in the controlled mode.

Besides soccer fans there always is normal pedestrian traffic at the station. Crucially, soccer fans will meet with a counterflow on the shortest and preferred route from the arrival area to the trains. We estimate the counterflow from data of a field study in 2020 [21]. It is seen as black trajectories in Figure 6.

Every two seconds, the controller can generate route recommendations that are disseminated via direct communication, using LTE sidelink, through the network. It recommends the least congested alternative route if and only if the direct route is the most congested route. Since the shortest route will almost always be the most congested, while Bayern München soccer fans keep arriving, there is little danger of rapid alterations of contradicting suggestions.

The survey in [5] showed that adherence to route instructions of Bayern München soccer fans at metro

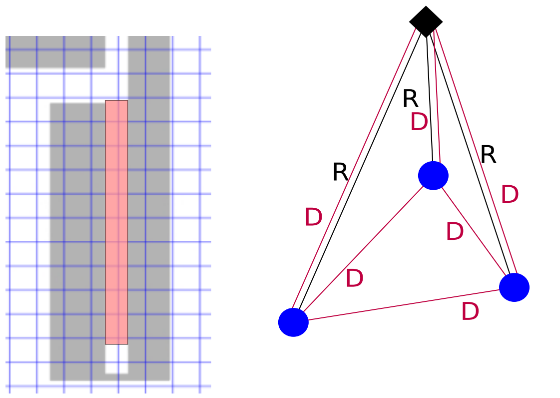

Figure 6. Guidance system with controller station. Left: Density values are averaged in the red area, here on the shortest route. The measurements are taken from the density map application that counts pedestrian for each cell. Each cell measures 1 m × 1 m. Left: The density information is relayed from agents to the relay station marked with a black diamond – black lines marked with an R. All agents (blue dots), directly interchange density information. These links are shown as red lines marked with a D. Density information and route recommendations are disseminated in separate mobile apps using LTE sidelink communication in the controlled mode. Figure adapted from Mayr [20].

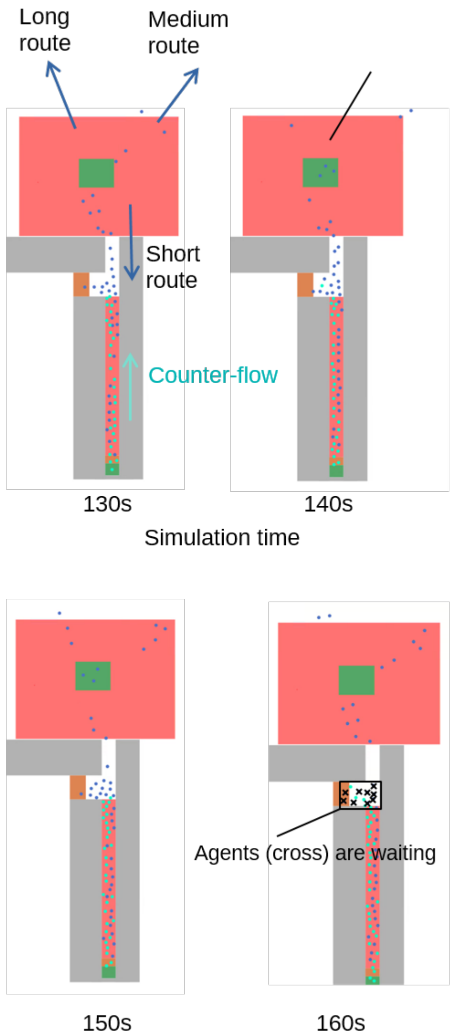

Figure 7. Resolving congestion through redirecting pedestrians: close-ups on the simulation area. Without guidance, the short route is congested due to the counter-flow: a clump forms where some agents come to a stop in front of the route entrance. Figure adapted from Mayr [20].

station Münchner Freiheit improves if mobile messages display current congestion information, a directional arrow, and appeals to team spirit. The survey was conducted online with almost 1 000 soccer fans and a control group of faculty and staff of about 500 persons. We showed them variations of app designs. The base design simply displayed an arrow pointing to towards the suggested route. We then added and combined information on the congestion status en route and an appeal to the team spirit to foster compliance. Thus, we were able to compile realistic compliance distributions with respect to app designs that conveyed directional suggestions.

We use the compliance distributions for the most effective message design to inform our simulations, that is, to stochastically model route choice in a way that matches true adherence behavior at the metro station before a soccer match as closely as possible. This input results in an average adherence of about 40 % among app users. In addition to this, we assume that only 40 % of all pedestrians use the app. This means that, on average, only 16 % of all agents in our simulation are ready to deviate to a longer route when asked.

Figure 7 and Figure 8 show snapshots of a close-up on the simulation area. Without redirecting pedestrians, a clump forms where two flows meet (see Figure 7). But with guidance, and despite the counterflow, the clump dissolves (see Figure 8).

Indeed, severe congestion on the preferred route to the trains is significantly relieved from a level of service E to D. Density levels go down from about 1.3 person/m^2 to often below 1 person/m^2 (see Figure 9). In the presence of a serious background traffic in the counter direction, one cannot hope for much more. This shows that, under realistic assumptions, the system is capable of making pedestrian traffic safer and more comfortable.

4. Discussion and conclusion

A holistic crowd guidance system was proposed that detects and redirects crowds through mobile applications, integrating system components described and verified in earlier work: We harnessed direct mobile telecommunication technology for density sensing and information transmission. In the presence of congestion, the least dense route is recommended to new arrivals to the area. Also, the mobile app was designed in a way to foster compliance.

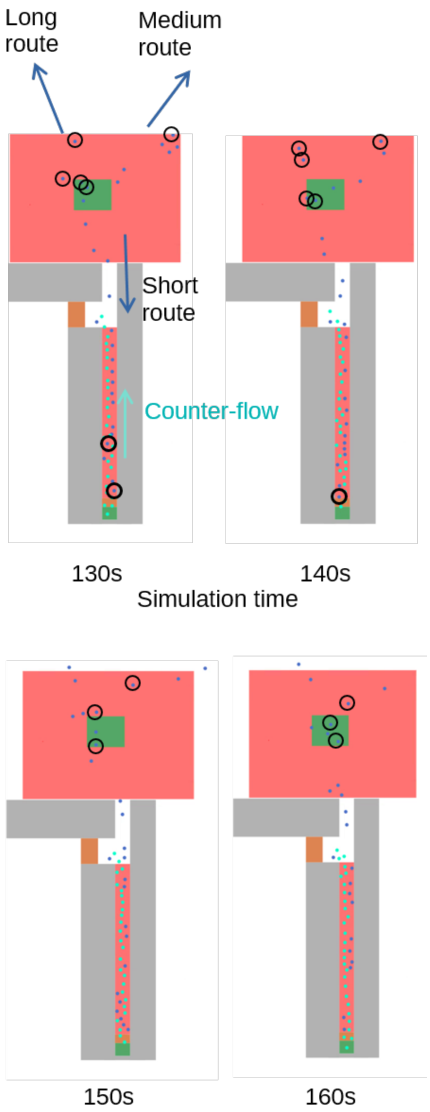

Figure 8. Resolving congestion through redirecting pedestrians: close-ups on the simulation area. With guidance, the route is less congested. Route recommendations are only displayed within the arrival area. Informed agents are marked with a circle: on average 40 % of them take the recommended long route, 35 % take the medium and 25 % take the short route. Figure adapted from Mayr [20].

To assess whether the overall system is effective and scales to realistic scenarios, we conceptualized and tested it as an integrated whole. We conducted a simulation study of crowd guidance at metro station Münchner Freiheit before a soccer match, making traffic assumptions based on a field study and taking adherence behaviour from a survey with almost 1 000 soccer fans. We argue that, with this, we get as close as possible to the behavior of the real system with respect to scale of the location, to crowd size, to mobile communication traffic load and to people's reaction to instructions.

We showed that, with the proposed system, one can redirect crowds and resolve safety-critical congestion

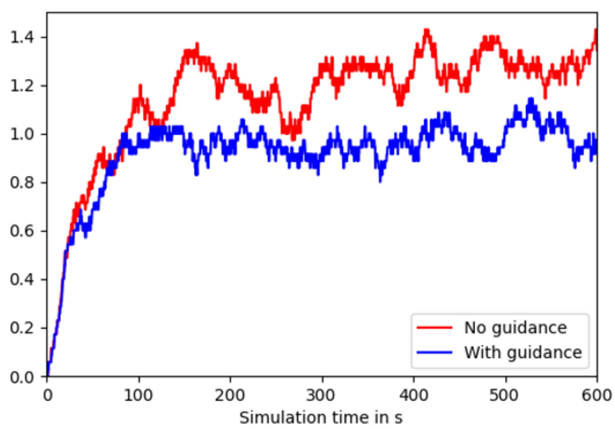

Figure 9. Congestion relief through crowd guidance on the preferred route to trains. Red: density without guidance system in person/m^2. Blue: density with guidance. We assume 40 % app usage. Compliance among app users is 40 % on average according survey. Figure adapted from Mayr [20].

even when making realistic assumptions on how many people in the crowd use the technology.

We argue that our studies make a strong case for manufacturers to speed up the roll-out of those system components that enable sensing and transmitting information through direct communication. But even if we have to wait for another few years for widespread availability of such smart phones, we believe that we have also shown that guiding people through an automatic system is much more feasible than crowd managers might fear. In our eyes, the key for success lies in simplicity of both, the instructions and the guidance algorithm, so that the system can deal with people's low adherence to instructions.

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