Simulation of Downhill Skiing Areas

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Abstract Based on video analysis of downhill skiing areas a model for ski traffic is developed. The video analysis uses `PeTrack` to determine the trajectories of individual skiers which are then statistically analysed. A stochastic cellular automaton model is proposed that can reproduce the basic observed features. The empirical data are used for validation and calibration of the model. In the future, the model may help to analyse comfort and safety on skiing slopes, especially the risk of collisions.

Keywords Self-driven particles · model calibration · cellular automata · trajectories

1 Introduction

Skiing is arguably one of the most popular recreational winter sports, both as *alpine (downhill) skiing* and *nordic (cross-country) skiing*. Due to global warming and less snowfall in recent years, the number of open ski slopes and resorts is decreasing [1]. This leads to potential over-crowding of skiing areas and thus less comfort and higher risk for the skiers [2]. Therefore, the available areas need to be used more efficiently. At this point, experiences made with crowd management [3] can be used as guiding principle.

Up to now, skiing has not been studied extensively from a traffic point of view. One notable exception is the work [4] on cross-country skiing. Here the motion is basically 1-dimensional, similar to a multi-lane highway. It uses a variant of the Intelligent Driver Model [5] to reproduce the occurrence of congestion and stop-and-go waves by taking into account uphill gradients and course geometry. In contrast to cross-country skiing, downhill skiing has more similarities with pedestrian dynamics. It is not lane-based and the motion is truly 2-dimensional. Furthermore, collision avoidance is an important factor for determining speed and direction of motion.

A physics-based model for downhill skiing has first been introduced in [6]. It uses the social-force model as a starting point and incorporates physical and social forces to determine the dynamics of the individual skiers. Physical forces have been included in much detail, especially the gravitational forces considering the slope and centripetal forces originating in turns of the trajectory. By taking into account the specific topology of the course, areas of potential higher risk for collisions may be identified. The model was further extended, e.g. by including more detailed social forces, and investigated in [7, 8]. One important finding of these studies is the importance of inhomogeneities, e.g. in the skill of the skiers, for more realistic results.

Here we follow a slightly different approach. A cellular automaton based model for downhill (alpine) skiing is introduced. Similar to the floor field model [9] for pedestrians, its dynamics is defined by transition probabilities to neighbouring cells which depend on the local situation in the neighbourhood of the agent. Cellular automata allow to easily incorporate effects like emotional states, wish for comfort and safety etc. which would be difficult to capture by forces. The model can be extended to make it more realistic by including other relevant aspects, e.g. anticipatory behavior for collision avoidance.

We use video footage from downhill skiing areas to determine typical properties of the skier's trajectory both qualitatively and quantitatively using `PeTrack` [10]. In contrast to earlier work we want to focus more on collective properties, i.e. traffic properties, than on the detailed description of the individual motion. This allows to study safety and comfort which are important demands for downhill skiing areas. High densities reduce comfort and lead to an increasing risk of accidents through collisions, especially at slope intersections [2]. We want to investigate the influence of various factors on the safety of skiers, e.g. density, skill levels, average speed and slope design. The further development of this simulation model could help to introduce comfort and safety measures in ski areas, e.g. improving the slope guidance system, crowd management, slope and intersection design.

2 Pedestrian Traffic vs Skier Traffic

Alpine skier traffic is basically 2-dimensional, similar to pedestrian motion, and only uphill motion is very rare. In contrast to vehicular traffic, skiers do not have to move in prescribed lanes. However, for safety reasons certain rules are obligatory, e.g. the ten FIS Rules, and have influence on skiers motion.

Besides these similarities, which indicate that similar model approaches are applicable for pedestrians and skiers, there are important differences. The dynamics of skiers is very much determined by inertia effects whereas for pedestrians inertia is not so relevant since the direction of motion can be changed quickly. For practical applications, e.g. safety analysis, the heterogeneity of the agents needs to be taken into account, especially in skill and experience, which leads to different speeds and trajectory types of the skiers.

It is expected that the risk for collisions increases strongly already at intermediate densities. In Austria, approximately 8% of all hospital-treated injuries occur due to collisions [11]. Preventing collisions is of high importance as they are often associated with severe injuries, e.g. fractures, internal injuries and concussions [12]. Typically such collisions occur when faster skiers intend to overtake slower ones or are avoiding a standing person or group. Additionally, topography and slope design have influence on the frequency of collisions. At intersections and behind rollers (part of slopes with limited view) the risk of collision becomes greater. One of the future goals is to determine a critical density where the number of such accidents (or close encounters) increases substantially. This would allow control measures that prevent reaching this critical density in order to increase safety and comfort. In this early stage of our work, however, interactions between skiers, which are essential to study collisions are not yet considered and the focus is initially on low density systems and the individual trajectories.

3 Data Collection and Analysis

For validation and calibration of the model, video footage from different slopes in the downhill skiing resort Grosseck-Speiereck in Austria is analyzed using `PeTrack` [10] which allows to determine trajectories for individual skiers.

In a first step, we have identified different classes of collective motion. Besides individual skiers (Fig. 1, left), several types of groups with 2-5 individuals have been observed who move at relatively close distance on similar trajectories (Fig. 1, right).

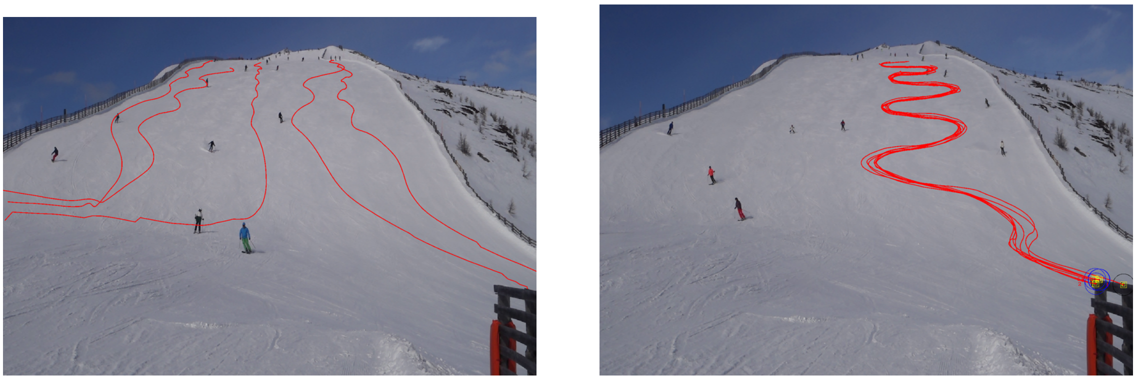

Figure 1 Left: Trajectories of individual skiers; Right: Trajectories of a skiing instructor with several pupils.

Further classification criteria of trajectories are based on velocity, the frequency of turning and the width of the trajectories. All these factors will be relevant when considering safety aspects. In general, they can change along the trajectory, depending on the slope, local density etc. In this early stage of our work we focus on a small area of the ski slope for which these factors can be considered constant. Furthermore the inclusion of effects from camera perspective are greatly simplified when extracting data for the trajectories.

The investigation of the statistical properties of the trajectories is currently performed, but more data are needed for reliable quantitative results. Based on qualitative observations in the video material a few interesting quantities which require detailed study have already been identified.

- Shape of trajectory, e.g. distance between turning points in horizontal direction. This corresponds to an effective width of the trajectory which is relevant e.g. for the perceived density.
- Correlations between speed and shape of trajectory, e.g. the distance between turns in vertical direction. This is correlated with the speed and the propensity to assume risks. The video material indicates that faster skiers move on straighter paths with longer vertical distance between turns to make optimal use of gravity for acceleration.
- Distribution of average speeds which is potentially related to the distribution of skill levels of skiers.
- Speed distribution along trajectory, i.e. the variability of the individual speed.
- Minimum distance to other agents (who are not members of the same group) and the edges of the slope during motion. This quantity reflects the risk behavior and is relevant for safety aspects.

Another interesting quantity related to traffic aspects is the fundamental diagram. However, it is unclear to deduce a meaningful definition of a fundamental diagram from the nature of the trajectories.

4 Modeling

Simulations using validated and calibrated models generate a statistical basis for better predictions of risk events. Simple model approaches that are flexible enough to allow incorporation of various relevant factors can help to identify problem areas. The experience with pedestrian motion has shown that cellular automata (CA) models satisfy these requirements and even allow to include psychological effects. In CA, space and time are discretized, e.g. the slope is divided into small cells which represent the typical space requirement of a skier. A reasonable size for the timestep is of the order of the reaction time of an agent.

A natural starting point would be a model based on a simple random walk where skiers move only downhill diagonally to the left or right neighbor cell, i.e. from position (x,y) to position $(x-1,y+1)$ or $(x+1,y+1)$. Here the coordinate y increases downhill. Not surprisingly this model is too simple to generate realistic trajectories which e.g. are much less regular than the empirical ones.

Therefore we introduce a different cellular automaton approach. The state of each skier can be described by its position (x,y) and a “memory” encoding whether the skier is in a left or right curve (right = false/true), which implements the principle of inertia (no instant left turning after being on a right turn).

Initially, the skiers are placed with a randomly chosen x-position and $y=0$. In each update, left $(x \to x-1)$ or right $(x \to x+1)$ steps occur with the probability p_l and p_r, respectively, and downward movement $(y \to y+1)$ with the complementary probability

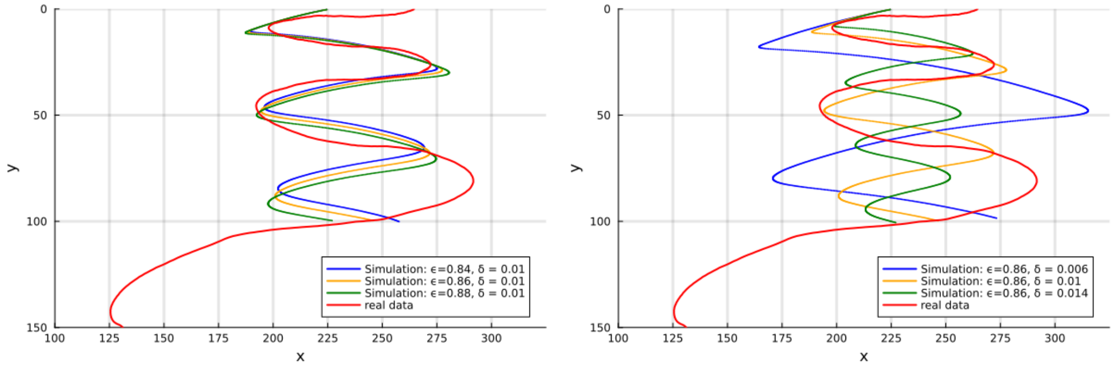

Figure 2 Comparison of simulations for different values of ε (left) and δ (right) with empirical trajectories extracted using `PeTrack`. One unit on the y-axis and x-axis corresponds to 5 and 1 cells in the cellular automaton, respectively. The simulation data has been averaged over 1000 runs of 1000 time steps. For each run, the skier is initialised in a "left" state with $p_r = p_l = 0.5$. The starting position is set close to the recorded trajectory ($(x,y) = (225,1)$).

$1 - p_l$ and $1 - p_r$, respectively. Upward movement ($y \to y-1$) is excluded due to the slope of the track. The update rule for one skier without interactions can be summarised (in pseudo-code) as follows:

$$\begin{array}{rllll} \text{if} & \text{right} = \text{true} & \& & \text{rand}() < p_r & \longrightarrow x = x+1; \quad p_r = p_r - \delta \cdot p_r \\ \text{elseif} & \text{right} = \text{true} & \& & \text{rand}() \geq p_r & \longrightarrow y = y+1; \begin{cases} p_l = p_l + \delta \cdot p_l, & p_l < \varepsilon \\ \text{right} = \text{false}, & p_l \geq \varepsilon \end{cases} \end{array}$$

$$\begin{array}{rllll} \text{if} & \text{right} = \text{false} & \& & \text{rand}() < p_l & \longrightarrow x = x-1; \quad p_l = p_l - \delta \cdot p_l \\ \text{elseif} & \text{right} = \text{false} & \& & \text{rand}() \geq p_l & \longrightarrow y = y+1; \begin{cases} p_r = p_r + \delta \cdot p_r, & p_r < \varepsilon \\ \text{right} = \text{true}, & p_r \geq \varepsilon \end{cases} \end{array}$$

The probability rand()$< p_r$ to move to the right again after a right move decreases with each time step by a factor $\delta \in]0,1]$. The same applies to a left moving skier. After a downwards move ($y \to y+1$) the probability p_l to enter a left curve increases up to a threshold ε. When this threshold $\varepsilon \in]0,1]$ is reached the skiers state ("memory") changes and right = false.

The parameter $\delta \in]0,1]$ controls the degree of probability change and $\varepsilon \in]0,1]$ controls the threshold. Both can be calibrated to change the characteristics of the trajectory, e.g. the curve's width. In Fig. 2 the real `PeTrack` data is compared with (averaged) trajectories obtained from simulations for different values of the parameters δ and ε.

In the presented form, all skiers move with constant speed. In future model extensions this simplification will be lifted by introducing velocity models with memory for both motion and speed. Preliminary results for such a model are promising. It also includes a friction parameter which - similar to δ - reduces velocity on left/right movement. In downward motion, speed is increased by gravity. The threshold parameter ε can then be reinterpreted as maximum or desired velocity of the skiers. Through these additional parameters the agreement between empirical and simulated trajectories will further be improved.

5 Next Steps

The results reported here are only the very first steps towards an understanding of the essential properties of downhill skiing areas. The focus was on a qualitative understanding of individual trajectories at low densities where interactions between skiers can be neglected. We have introduced a simple model which allows to reproduce the basic properties of individual trajectories even quantitatively.

In a next step, higher density situations are considered where interactions between the skiers become more relevant. This is challenging since on the available video material such situations are (luckily!) not very frequent due to relatively low densities so that currently the analysis of close encounters can mostly be done on a qualitative level only. We hope to obtain more empirical data at higher densities in the upcoming skiing season.

The absence of close encounters observation indicates that most skiers anticipate quite well, so that collisions are generally rather rare. Therefore in modeling, anticipation effects have to be considered where the skiers change their direction of motion and/or speed early in order to avoid close encounters. It is expected that the number of such encounters will depend strongly on density, heterogeneity of skill and risk propensity. In order to study these aspects quantitatively, both on an empirical and theoretical level, criteria for collisions or close encounters have to be developed.

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