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Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

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International Symposium of Transport Simulation (ISTS'18) and the International Workshop on Traffic Data Collection and its Standardization (IWTDCS'18)

Simulating interactions between pedestrians, Segway riders and cyclists in shared spaces using social force model

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Abstract

Segway and other two-wheeled personal mobility vehicles (PMVs) are gaining remarkable popularity as an alternative transport mode in urban environments particularly for short distance trips. The designs of shared sidewalks and implementation policies should be properly evaluated before authorizing PMVs on shared sidewalks, particularly in cities with high pedestrian and bicycle traffic. Properly calibrated microscopic simulation tools can facilitate such purposes. In this study, the applicability of social force model is tested.The findings suggest that, under uncongested situations, the avoidance patterns of Segway riders and cyclists are adequately captured by the calibrated social force model.

Keywords: Social force model; model calibration; pedestrians; personal mobility vehicles; bicycles; mixed traffic; microscopic simulation

1. Introduction

Personal mobility vehicles (PMVs), such as Segway, are emerging as an eco-friendly alternative transport mode for short distance trips both in indoor and outdoor environments. These vehicles use electrical energy stored in re-chargeable batteries and have been used in eco-tours in many cities around the world. PMVs provide numerous economic, environmental, and social benefits, such as reducing congestion in urban centers, reducing greenhouse emissions and providing a way of mobility for elderly and disabled pedestrians (Liu and Parthasarathy (2003), Shaheen and Finson (2003), Ulrich (2005)). Furthermore, users' attitudes and acceptability towards PMVs are also positive (Ando and Li (2012)). Thus, it can be expected that PMVs will be more common in urban spaces in the near future. It is not practical to provide separate spaces (e.g., exclusive lanes) for such vehicles in compacted sidewalks. Thus,

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other alternatives (e.g., share the space with pedestrians and cyclists) should be considered. That is, the designs of shared sidewalks and implementation policies should be properly evaluated before authorizing PMVs on these shared sidewalks, particularly in cities with high pedestrian and bicycle traffic.

Operational and safety aspects of PMVs in mixed traffic conditions have been investigated by several of previous studies using empirical data mainly collected through controlled experiments. Goodridge (2003) showed that the stopping sight distance (SSD) of a Segway that approaches at 20 km/h can vary from approximately 7.6 m to 12.5 m for different deceleration rates. Perception and reaction time of Segway riders have also been explored by previous studies for mixed aged riders (Landis et al. (2004)) and college-age riders (Goodridge (2003), Dias et al. (2017a)), under different conditions, e.g., general stopping conditions (Landis et al. (2004), Dias et al. (2017a)) and sudden stopping situations (Goodridge (2003), Dias et al. (2017a)). Through a controlled experiment Nishiuchi et al. (2010) verified that the safe avoidance distance of a standing pedestrian increases (approximately from 2.2 m to 5.5 m) when confronting a Segway approaching at different speeds ranging approximately from 5 km/h to 20 km/h. Miller et al. (2008) investigated the approaching and passing speeds and clearance distance of Segway riders when passing static roadside objects and walking pedestrians through a series of experiments. Dias and Iryo-Asano (2017) evaluated the collision risk of pedestrians and cyclists when followed by a Segway rider using time-to-collision (TTC) and potential index for collision with urgent deceleration (PICUD) indices.

All these experiment-based studies provide a general overview of the operational and safety aspects of PMVs under different mixed traffic situations. However, it is difficult to consider all possible scenarios, particularly critical or risky scenarios, in controlled experiments mainly due to safety concerns. Thus, simulation-based approaches may be more appealing to evaluate such critical scenarios. Further, designs of shared sidewalks and implementation policies could also be evaluated using properly calibrated simulation tools.

In an effort to simulate interactions between PMVs and pedestrians on shared spaces, Pham et al. (2015) adopted the idea of personal space. They introduced invasion ratio and crossing time of personal spaces of PMVs and pedestrians as indexes to describe the level of discomfort. Dias et al. (2017b) calibrated the parameters of a social force model specification (Johansson et al. (2007)) for Segway and pedestrian mixed traffic. Further, they used the calibrated model for evaluating the safe avoidance distance of pedestrians when confronting an approaching PMV (Dias et al. (2017c)). However, other possible interaction types on shared spaces (e.g., Segway-bicycle, bicycle-pedestrians) were not considered in their study. Further, statistical differences between parameters for different avoidance patterns in same interaction situation (i.e., when a pedestrian avoiding a Segway rider and when a Segway rider avoiding a pedestrian) were not discussed. This study aims at calibrating the same model for more complex scenarios, particularly Segway-bicycle and bicycle-pedestrian interactions. Data collected through controlled experiments are utilized to calibrate parameters of the model for different interaction types. Details of the experiment design and considered scenarios are discussed in the next section.

2. Experiments

These experiments were conducted on a sidewalk (width is approximately 4.2 m) at the Funabashi campus of Nihon University, Japan in October 2017. The PMV used in these experiments was Segway i2 model (details and specifications can be found in www.segway.com) that was developed in the United States and commercially available from 2006. Beginner as well as experienced Segway riders (with more than 6 months previous experience in riding a Segway) participated in this experiment. In this study the data only for experiences Segway riders were used. Mainly four interaction type were considered in these experiment scenarios as follows:

- A Segway rider avoids a cyclist (S-C)
- A Segway rider avoids a pedestrian (S-P)
- A cyclist avoids pedestrian (C-P)
- A cyclist avoids a cyclist (C-C)

The number of runs for C-S, S-P, C-P and C-C experiment scenarios were 8, 16, 22 and 12 respectively. The entire experiment series was video-recorded with overhead video cameras. Fig. 1 shows snapshots taken during several experiment scenarios. The position and time of each Segway rider, pedestrian and cyclist were extracted by manual

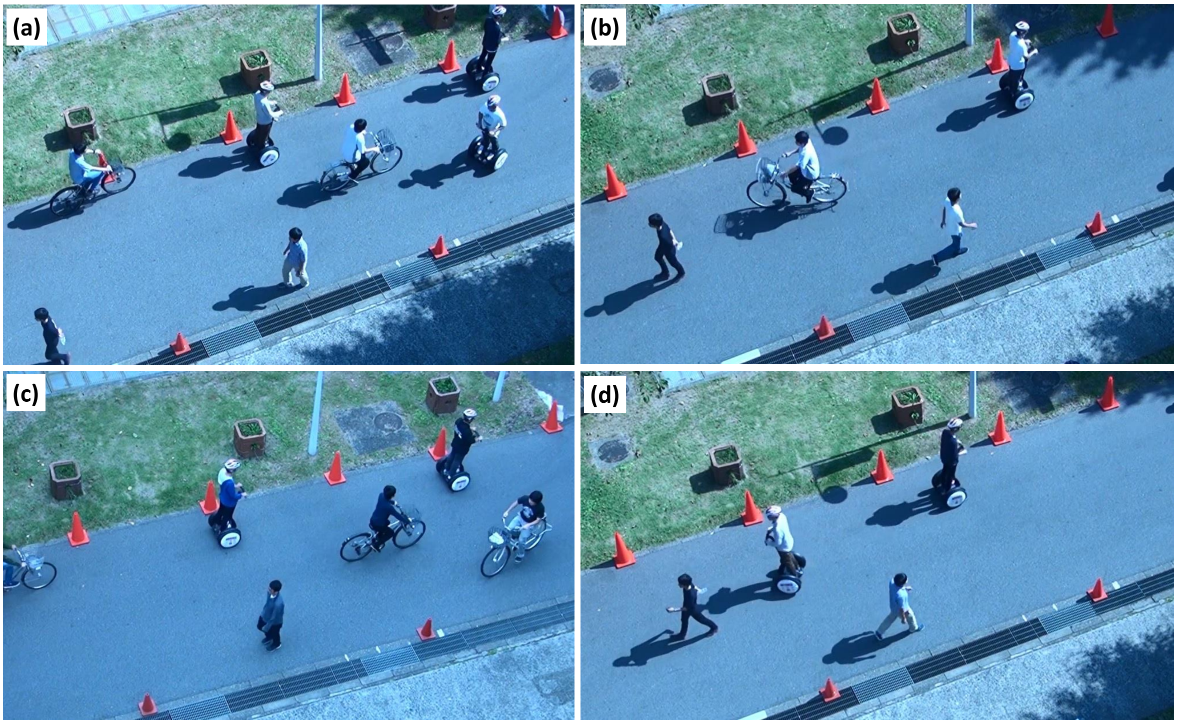

Fig. 1. Snapshots during experiment scenarios: (a) a Segway rider avoiding a cyclist; (b) a cyclist avoiding a pedestrian; (c) a cyclist avoiding a cyclist; (d) a Segway rider avoiding a pedestrian.

tracking and the coordinates were transformed (from pixel to meters) by projective transformation. The time resolution of the extracted trajectory data was 0.5 s. As previous studies have already calibrated the social force model for Segway-pedestrian interactions (Dias et al. (2017b)), this study only focused on the trajectory data for Segway-cyclist, cyclist-pedestrian and cyclist-cyclist interactions. I.e., interaction force parameters of the social force model are calibrated separately for those interaction types. The fundamentals of the conventional social force model are briefly discussed in the next section.

3. The social force model

In previous studies, different versions of social force model have been adopted to simulate different traffic mixes, such as cars and bicycles (Li et al. (2011)), cars and pedestrians (Schönauer et al. (2012), Anvari et al. (2016), Pascucci et al. (2015)), on shared spaces. Pedestrians' danger perception towards personal mobility vehicles has also been modelled using social force modelling concept (Hasegawa et al. (2018)). The social force model assumes that the pedestrians are subjected to physical and psychological forces. Thus, the acceleration (or deceleration) of an individual i at time t owing to those forces can be described as follows:

$$\frac{d\vec{v}_i(t)}{dt} = \frac{1}{\tau_i}(v_i{}^o\vec{e}_i - \vec{v}_i(t)) + \sum_{j(\neq i)} \vec{f}_{ij}(t) + \sum_{w} \vec{f}_{iw}(t) + \vec{\xi} \tag{1}$$

The social force model assumes that each individual attempts to move in the desired direction $\vec{e}_i$ with a desired speed $v_i{}^o$, and that he or she adapts the current velocity $\vec{v}_i(t)$ to the desired one within a certain time duration, which is characterized by the relaxation time τ_i. The terms $\vec{f}_{ij}(t)$ and $\vec{f}_{iw}(t)$ are repulsive force components used to keep a certain distance by pedestrian i from the surrounding pedestrians (j) and walls (w) respectively. The term $\vec{\xi}$ represents the fluctuations caused by the randomness.

Other forces were also used in the original model to describe the physical contacts in crowded conditions. However, those were omitted at this stage because we only focused on uncongested situations. Wall (or boundary) forces were also omitted as considered Segway riders and cyclists do not directly interact with boundaries.Considered force component are discussed in details in the following sub-sections.

3.1. Desired force

Pipes (1953) described that the acceleration of a vehicle can be described by the following expression:

$$v_i(t) = v_{o,i} - v_{o,i}\ exp\left(\frac{-t}{\tau_i}\right) \tag{2}$$

where, $v_i(t)$ is the speed at time t (measured from the start of the movement), $v_{o,i}$ is the desired speed and τ_i is the relaxation time.

The desired force component of the Eq. 1 can be obtained by differentiating Eq. 2 with respect to time and rearranging.

3.2. Repulsive forces caused by interactions

The elliptical specification suggested in Johansson et al. (2007) assumes that the interaction forces between the interacting agents i and j emerge via repulsive potentials. The repulsive force due to those repulsive potentials can be given as follows:

$$\vec{g}_{ij}(\vec{d}_{ij}) = A_i\ exp\left(\frac{-b_{ij}}{B_i}\right).\frac{||\vec{d}_{ij}|| + ||\vec{d}_{ij} - \vec{y}_{ij}||}{2b_{ij}}.\frac{1}{2}\left(\frac{\vec{d}_{ij}}{||\vec{d}_{ij}||} + \frac{\vec{d}_{ij} - \vec{y}_{ij}}{||\vec{d}_{ij} - \vec{y}_{ij}||}\right) \tag{3}$$

where, b_{ij} is the semi-minor axis of the ellipse and $\vec{y}_{ij}$ is the anticipation distance which are determined as follows:

$$2b_{ij} = \sqrt{(||\vec{d}_{ij}|| + ||\vec{d}_{ij} - \vec{y}_{ij}||)^2 - ||\vec{y}_{ij}||^2} \tag{4}$$

$$\vec{y}_{ij} = (\vec{v}_j - \vec{v}_i)\Delta t \tag{5}$$

where, $\vec{d}_{ij}$ is the displacement vector pointed from individual j to i, $\vec{v}_i$ and $\vec{v}_j$ are the velocity vectors of individual i and j, Δt is the anticipation time which represents how far an individual interpolate current movement linearly into the future, A_i, B_i are parameters.

Eq. 3, 4 and 5 explain that the repulsive force on individual i is derived from an ellipse-shaped potential with the semi major axis in the movement direction of individual j. Apart from this repulsive force, which is a function of displacement and relative speed between individuals i and j, the anisotropy effect or the effect of relative orientation is modelled as follows:

$$w(\varphi_{ij,t}) = \left(\lambda_i + (1 - \lambda_i)\frac{1 + cos(\varphi_{ij,t})}{2}\right) \tag{6}$$

where, $\varphi_{ij,t}$ is the angle between the normalized distance vector and the motion direction of the considered pedestrian i and $\lambda_i (0 \le \lambda_i \le 1)$ is a parameter. In this study, assuming the complete effect from the interaction angle, we set $\lambda_i = 0$.

By combining Eq. 3 and Eq. 6, the complete equation for the repulsive force between the shared space users i and j, can be given as follows:

$$\vec{f}_{ij}(\vec{d}_{ij}) = w(\varphi_{ij,t}).\vec{g}_{ij}(\vec{d}_{ij}) \tag{7}$$

Eq. 2 to 6 explain that there are 4 parameters to be calibrated (i.e., τ, A, B, and Δt) for Segway riders, pedestrians and cyclists separately. Other than these parameters, desired speeds for each user type ($v_i{}^o$) should also be obtained.

The trajectories collected through the controlled experiments discussed in Section 2 were used to calibrate these parameters. The details of the calibration methods are described in the following section.

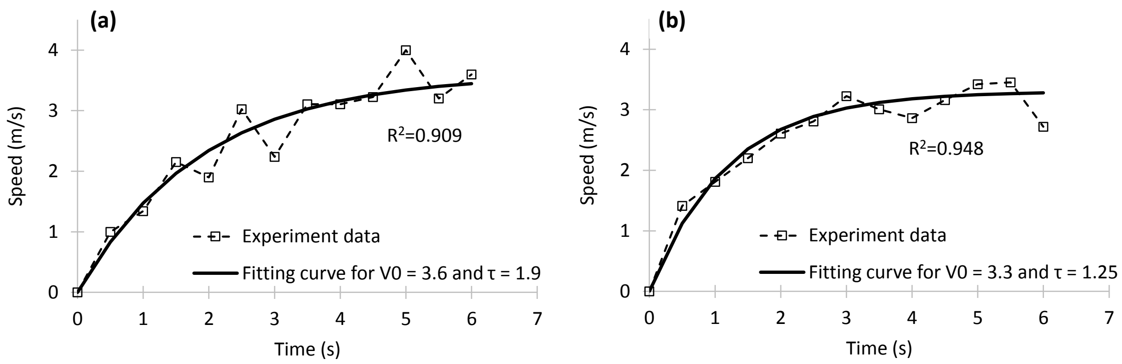

Fig. 2. Calibration of desired force parameters for: (a) a Segway rider; (b) a cyclist.

4. Model calibration

4.1. Calibration of desired force parameters

Desired force parameters (i.e.,v_i^o and τ) were calibrated for each pedestrian, Segway rider and cyclist by fitting the empirical data to Eq. 2. Fig. 2 depicts two examples for the calibration of v_i^o and τ values for a Segway rider and a cyclist. Average values with standard deviations (SD) estimated for Segway riders and cyclists (for different mixed traffic situations) are tabulated in Table 1.

Table 1. Calibrated desired force parameters for Segway riders and cyclists in different scenarios.

Parameter	Segway rider (avoiding a cyclist)	Cyclist (avoiding a pedestrian)	Cyclist (avoiding a cyclist)
$v_i^o(\pm SD)$ in m/s	3.18(±0.58)	3.44(±0.16)	2.86(±0.61)
$\tau(\pm SD)$ in s	2.15(±0.24)	1.67(±0.18)	1.35(±0.13)

The calibrated average v_i^o and τ values in this study for experienced Segway riders are consistent with the values reported in Dias et al. (2017c) which were 3.32(±0.74) m/s and 2.25(±0.37) s respectively. From Table 1 it can be noted that average τ value for Segway riders is larger than that for cyclists. This means that a cyclist can achieve the desired speed faster compared to a Segway rider. Further, it was noted that cyclists tend to keep a lower average desired speed when they are interacting with cyclists compared to the situations when they are interacting with pedestrians. Average speeds of cyclists when interacting with pedestrians and cyclists were statistically significant (Mann-Whitney U test z-score = 3.4352, p-value = 0.0006).

4.2. Calibration of interaction force parameters

Cross-entropy (CE) method (De Boer et al. (2005)) was adopted to calibrated interaction force parameters (i.e., A, B, and Δt). During the calibration process, considered cyclist or Segway rider (of which the parameters were calibrated) was moved according to the social force model while surrounding pedestrians, Segway riders and cyclists were moved exactly in the same way as the corresponding experimental trajectories. Main steps in CE method followed in this study are summarized below:
Step 1: v_i^o and τ for the considered Segway rider or the cyclist were set based on the method described in previous section. Trajectories of surrounding pedestrians or Segway riders were also set as inputs.
Step 2: The N (= 100 in this study) combinations of the parameters, which followed uniform distributions, were generated. Initial ranges of the parameters for A, B and Δt were set as [0, 5], [0, 5] and [0, 10] respectively. An N number of random trajectories were simulated based on these parameter combinations and other properties set under Step 1.

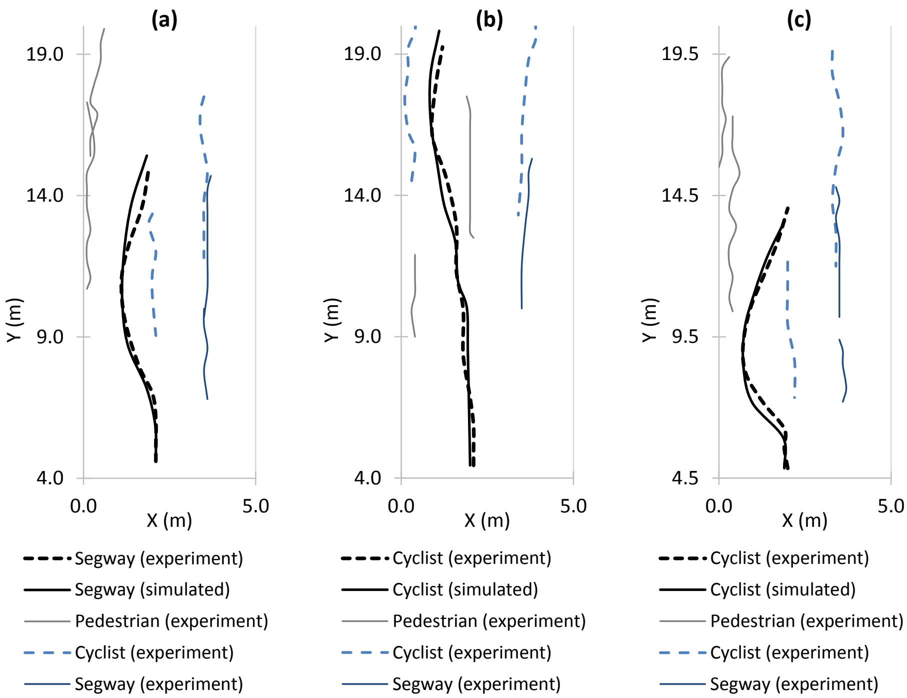

Fig. 3. Comparison of the simulated and experimental trajectories for: (a) a Segway rider avoiding a cyclist; (b) a cyclist avoiding a pedestrian; (c) a cyclist avoiding a cyclist.

Time step for all simulated and not simulated trajectories was set as 0.5 s (i.e., similar to experimental trajectories).
Step 3: The average lateral displacement error ($\bar{\epsilon}_x$) for each simulated trajectory under Step 2 was calculated as follows:

$$\bar{\epsilon}_x = Average|X_{Simulated,t} - X_{Experiment,t}| \tag{8}$$

where, $X_{Simulated,t}$ and $X_{Experiment,t}$ are the lateral position (X-coordinate) of the simulated and corresponding experimental trajectories at the same time t, respectively.
Step 4: The simulated trajectories were then sorted in ascending order based on the average absolute lateral displacement error estimated using Eq. 8. The ranges of the initial ρ parameters (= 70% in this study) of the trajectories were considered to generate the random trajectories (similar to Step 2) for the next iteration. The iterations (i.e., Steps 2 to 4) were stopped when the average displacement errors for all the simulated trajectories were not improved than a certain threshold, which was set as 0.05 m. That is, visually, all simulated N trajectories are overlapped at the final iteration. Average of the each parameter set was considered as the calibrated parameter values.

Parameters were calibrated for each Segway rider (avoiding a cyclist), each cyclist (avoding a pedestrian) and each cyclist (avoiding a cyclist). The average values with standard deviations for these interaction types are compared in Table 2.

Table 2. Calibrated interaction force parameters for Segway riders and cyclists for different interacting situations.

Parameter	Segway rider (avoiding a cyclist)	Cyclist (avoiding a pedestrian)	Cyclist (avoiding a cyclist)
A in m/s^2	1.90(±0.60)	1.76(±0.35)	1.38(±0.20)
B in m	0.83(±0.14)	1.15(±0.41)	1.93(±0.28)
Δt in s	3.69(±0.85)	1.72(±0.32)	2.58(±0.72)

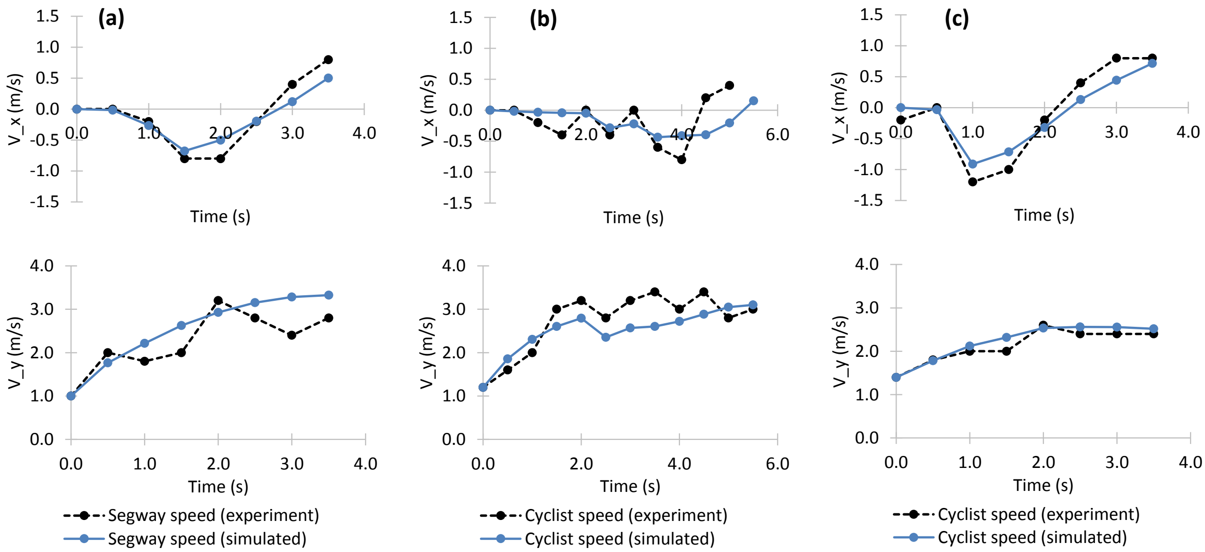

Fig. 4. Comparison of the simulated and experimental lateral (up) and longitudinal (down) speed profiles for: (a) a Segway rider avoiding a cyclist; (b) a cyclist avoiding a pedestrian; (c) a cyclist avoiding a cyclist (see Fig. 3 for corresponding trajectories).

Table 2 explains that the calibrated parameter values are different for different shared space users under different interaction types. Mann-Whitney U test confirmed that, except average A values for Segway riders (avoiding a cyclist) and cyclist (avoiding a pedestrian), average values for each parameter under different interaction combinations are statistically significant. It can be noted that the anticipation time (Δt) are generally lower for Cyclists. This observation indicates that the the time (and distance) interpolated by a cyclist is comparably lower than that of a Segway rider. In other words, cyclists tend to avoid pedestrians or cyclists interacting with them at closer ranges and that could further be confirmed by observing video recodrings of the experiment. Average Δt for Segway rider avoiding a pedestrian ($2.47(\pm 1.08)s$) calibrated in Dias et al. (2017c) and cyclist avoiding a pedestrian (Table 2) were also found to be significantly different (Mann-Whitney U test z-score = 2.130, p-value = 0.0332). Lateral control could also have impacts on such behaviors. I.e., compared to a Segway rider, it is relatively easy for a cyclist to suddenly change the direction without slowing down.

Fig. 3 (a), (b) and (c) compare simulated trajectories with corresponding experimental trajectories for a Segway avoiding a cyclist, a cyclist avoiding a pedestrian and a cyclist avoding a cyclist situations respectively for 3 experiment runs. Corresponding speed profiles for the same experiment runs are depicted in Fig. 4. The average absolute lateral displacement error values for Segway avoiding cyclist, cyclist avoiding pedestrian and cyclist avoiding a cyclist scenarios were estimated based on Eq. 8 and those were 0.19 m, 0.22 m and 0.25 m respectively. Fig. 3, 4 and associated error statistics explain that the behaviors of Segway riders and cyclist for the considered mixed traffic situations can adequately be reproduced by the calibrated social force model.

It should be noted that a limited sample sizes or experiment runs (8 runs for a Segway avoiding a cyclist scenario, 22 runs for a cyclist avoiding a pedestrian scenario and12 runs for a cyclist avoiding a cyclist scenario) were available. Thus, additional data under different experiment settings are required to verify the model performances and to validate the calibratied model.

5. Conclusions

In this study, the parameters of the social force model were calibrated to simulate Segway rider and cyclists behavior in different mixed traffic situations under uncongested conditions. Trajectory data collected through controlled experiments conducted under different Segway, cyclist and pedestrian interacting situations were used for the calibration. The calibration method adopted in this study was the cross-entropy method. Qualitative and quantitative comparisons of simulated and corresponding experimental trajectories explained that the calibrated model can sufficiently reproduce movements and interactions of Segway riders and cyclists when sharing the space with different mixed traffic.

In this study, the original formulation of the social was used as it is. I.e., only the parameters were calibrated for interactions between different agent types without modifying the model. Therefore, the same longitudinal behavior and lateral behavior were assumed for all simulated agents. However, due to maneuverability and restrictions in movements, lateral and longitudinal behaviors of bicycles and Segway could be remarkably different. Such issues should be carefully considered in further modifications or enhancements to the social force model to better simulate vehicle movements using the social force model that was originally proposed for pedestrians.

Under future studies, based on the findings of this study and related past studies, a mixed traffic simulator should be developed to verify the reproducibility of the Segway, cyclist and pedestrian behaviors under more complex interacting situations. Further, macroscopic characteristics of different mixed traffic flows should also be evaluated.

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Paper ID: 46

Simulating Interactions between Pedestrians, Segway Riders and Cyclists in Shared Spaces using Social Force Model

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Supplementary statement responding to reviewers' comments:

We would like to thank the reviewers for their valuable comments as those were helpful for reorganizing the paper. Responses for reviewer's comments are listed as follows.

REVIEWER 1:

[Comment 1]

The study presents analysis on the interaction between segways, cyclists and pedestrians. Although, the topic is intersecting and relevant, however the structure and flow the paper is not well prepared. I can not identify the contribution or the significance of this study especially that I think the considered scenarios are not selected and defended properly. The objective and significance was not clear which led to weak conclusion without generalized results.

[Response]

Objective of this study is to test the applicability of social force model, which is a pedestrian simulation model, for simulating Segway-bicycle, bicycle-pedestrian and bicycle-bicycle interactions. We microscopically calibrate the model and show that under uncongested situations the avoidance patterns are adequately captured. Considering reviewer's comment we have clearly mentioned such points in the revised manuscript (abstract and last paragraph of introduction).

[Comment 2]

1) Four scenarios are defined in page 2 "Section 2 experiments", however in each of these scenarios are the objectives moving in the same direction or in opposite direction. The calibrated parameters will be different since the maneuvers are different. Fig. 1 shows different situations, one time in same direction and another in opposite direction.

[Response]

As we discussed in Section 3.2 we used the elliptical specification suggested by Johansson et al. (2007). In that specification parameters will not be different depending on the direction of the interacting pedestrian. Further, the effect of relative angle (or orientation) is taken care by the weighting factor in Eq. (6).

[Comment 3]

2) yes authors assumed 4 scenarios in page 2 "Section 2 experiments", but the only presented results for 3 of them (Figure 3 and 4). No discussion of Segway avoiding pedestrians. This was confusing.

[Response]

One of our precious studies calibrated parameters for Segway-pedestrian interactions and therefore, we omitted that in this paper. However, considering reviewer's comments we have added such points (below Figure 1).

[Comment 4]

3) what is the platform used for manual tracking.

[Response]

It is the manual recording of the image coordinates (in pixel pixel) and the converted to ground coordinates (in m) by projective transformation. Such points are mentioned in the revised manuscript.

[Comment 5]

4) In page 5 under Table 1, authors stated "From Table 1 it can be noted that average t value for Segway is lower than that for cyclists". I think it should be opposite Segway has higher t than cyclists.

[Response]

That is our mistake and thank you for pointing out that. We have made corrections in the revised manuscript.

[Comment 6]

5) In page 5, section 4.2, authors stated "...surrounding pedestrians, Segway riders and cyclists were moved exactly in the same way" what that mean?

[Response]

This means that we simulated only the considered cyclist or the Segway rider. Surrounding agents' trajectories were not simulated and kept as it is (similar to the calibration process presented in Johannsson et al. (2007)).

REVIEWER 2:

[Comment 1]

The number of participants in the experiment and the number of runs of each experiment should be described in Chapter 2.

[Response]

We thank the reviewer for pointing out such unclear points and we have included such points in the revised manuscript.