Generalization of the Social Force Model for Mixed Traffic Contexts including Personal Mobility Devices

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SHORT SUMMARY

The emergence of Personal Mobility Devices (PMDs), more specifically e-scooters, has transformed the way people move in large cities. These devices can be used in contexts where they interact with low, medium and high pedestrian flows; on cycle paths; but also on roads where they directly interact with motor vehicles. In particular, their coexistence with other soft mobility modes has not been sufficiently explored but is critical for safety and other reasons. In this paper, we propose a novel modeling approach for the description of the movements and interactions among PMDs, cyclists, and pedestrians extending the Social Force Model and introducing specific vehicle dynamics. The novel model is calibrated and validated using a trajectory database obtained through experimentation in a semi-controlled environment. The results show that the proposed model is able to accurately describe all road user interactions and significantly reduces the error in the estimation of the lateral movements.

Keywords: Social Force Model, vulnerable users, e-scooters, bicycles, pedestrians, PMDs.

1. INTRODUCTION

Personal Mobility Devices (PMDs) or micromobility vehicles emerge as a promising solution towards reducing road traffic and its externalities: congestion, air and noise pollution, traffic accidents, and so on. PMDs are easy-to-carry and/or easy-to-push, they may range from lighter rollers and skis to heaviest two-wheeled self-balancing personal transporters (Christoforou, et al., 2021). Their usage has been intensified over the last years, particularly in dense urban areas. Among all PMDs, e-scooters seem to dominate the market showing a surging popularity that has been accelerated by the pandemic COVID-19 resulting to the deployment of large free-floating fleets worldwide.

At present, we can observe that PMDs share the road space with bicycles and pedestrians on sidewalks or cycle paths, as well as with private cars, trucks and buses when moving on mixed traffic lanes. This ambivalent road behavior along with specific movement dynamics (acceleration and braking force, maximal speed) make e-scooters a hybrid moving object that can be seen either as an 'augmented pedestrian' or as a 'reduced motor vehicle'. The behavior and nature of e-scooters at the microscopic level has not been sufficiently explored and studied. On the contrary, several studies have focused on the vulnerability of e-scooter riders and the severity of accidents involving e-scooters when riding on the pavement (Shah, et al., 2021).

Of particular interest is the case when e-scooters move on public spaces used also by pedestrians and simple (i.e. non electric) bikes. Evidence suggests that, in this case, e-scooters present a threat to 'more vulnerable' users (Bozzi & Aguilera, 2021) such as pedestrians and cyclists who move at lower speeds, have smaller mass and lower acceleration / braking capabilities. Besides, this is the reason why many local authorities, including the Municipality of Paris, imposed severe restrictions on the movement of e-scooters on sidewalks and pedestrianized areas. However, robust tools to evaluate the risk of coexistence and formulate evidence-based policies are still missing. To the best of our knowledge, a comprehensive traffic model analyzing the coexistence of pedestrians, bicycles and e-scooters has not been proposed yet. This may be due to the lack of specific models and large databases as those used for car traffic.

In this paper, we propose the use of the Social Force Model (Helbing & Molnar, 1995) to describe the movement and interactions among e-scooters, cyclists, and pedestrians. We extend the baseline model by a detailed estimation of the force applied by e-scooters on the other road users. We calibrate and validate the new model formulation on a dataset of trajectories obtained through an experimental procedure in a semi-controlled environment.

2. METHODOLOGY

Experiment and data

The trajectory database was generated using experimental data. The open track experiment took place in autumn 2021 at the campus of the University of Patras, Greece, with the participation of over 100 road users including cyclists, e-scooter riders and pedestrians. The experiment was conducted in a semi-controlled environment as non-participants could not interfere but participants could move freely on the road space following the general guidelines of the experimental scenarios. The scenarios resulted by varying (i) the direction of the movement, (ii) the type of infrastructure (cycle lane, path or sidewalk), and (iii) the width of the lane/sidewalks.

The experiment was filmed and the extraction of the trajectories was achieved automatically through image processing and appropriate post-processing as in (Valero, et al., 2020).
The final database contains the position (x,y) of each of the road users at each time step and was used to first calibrate and then validate the extension of the model proposed below.

Proposed model

The Social Force Model (SFM) is based on Newtonian equations. It was first proposed by (Helbing & Molnar, 1995) and has been extensively used since allowing the simulation of large number of people moving under normal or emergency situations. SFM suggests that the direction and magnitude of a pedestrian's movement is a result of all the forces with which the pedestrian interacts. The resultant force $F_i(t)$ at time t, can be expressed as follows:

$$F_i(t) = m_i \frac{dv_i(t)}{dt} = f_i^d + \sum_{j(\neq i)} f_{ij} + \sum_{w} f_{iw} + \xi_i \qquad (1)$$

Where f_i^a is the force to the desired destination of pedestrian i, f_{ij} is the repulsive force of pedestrian j to pedestrian i, f_{iw} is the force from walls exerted on the pedestrian i and ξ_i is a fluctuation term that take into account random variations of the behavior of pedestrian i.

Initially proposed for pedestrian movement, SFM has been recently extended and applied in other cases presenting similarities with pedestrians. The model of equation 1 was calibrated in by (Dias, et al., 2018) for the case of segways (i.e. a heavier PMD) and by (Valero, et al., 2020) for the case of e-scooters. The results show that SFM is indeed appropriate for modeling PMDs movement. Nevertheless, the error measured for lateral behavior was found to be high and the group force, as suggested by (Moussaïd, et al., 2010) was not considered but could be significant. In order to consider the group force f_{ig}, we use here the extended model proposed by (Moussaïd, et al., 2010), in which the term f_{ig} describes the response of pedestrian i to other group members.

$$F_i(t) = m_i \frac{dv_i(t)}{dt} = f_i^d + \sum_{j(\neq i)} f_{ij} + \sum_{w} f_{iw} + \sum_{g} f_{ig} + \xi_i \qquad (2)$$

In addition, the Social Force exerted by a car on a pedestrian has been studied in (Yang, et al., 2018). In building on the model described by Eq. 2 and (Yang, et al., 2018), we propose a generalization (Eq. 3) in order to model the movements on shared spaces used by pedestrians, bicycles and PMDs. For this purpose, we propose to include the force applied by a PMD f_i^{PMD}on each road user (pedestrian, bicycle or other PMDs). In addition, we included a calibration parameter $\gamma_i(f_i^{PMD})\ \epsilon\ [0,1]$ that allows a correction factor to be applied to the f_i^d force to the desired position.

$$F_i(t) = f_i^d \sum_{PMD} \gamma_i(f_i^{PMD}) + \sum_{PMD} f_i^{PMD} + \sum_{j(\neq i)} f_{ij} + \sum_{w} f_{iw} + \sum_{g} f_{ig} + \xi_i \qquad (3)$$

Where now, $F_i(t)$ represents the resultant force applied on a road user type (Pedestrian, Bicycle or PMD) at a time t.

To define f_i^{PMD}, we divided the zone of influence into three areas (see Fig. 1.): (i) Field of view area, this is the area where the bicycle or PMD user can actually see another road user. (ii) Body area, it is the area lateral to the road user, i.e. there is no longitudinal force applied to the road user and (iii) Rear area, it is the area behind the bicycle or PMD.

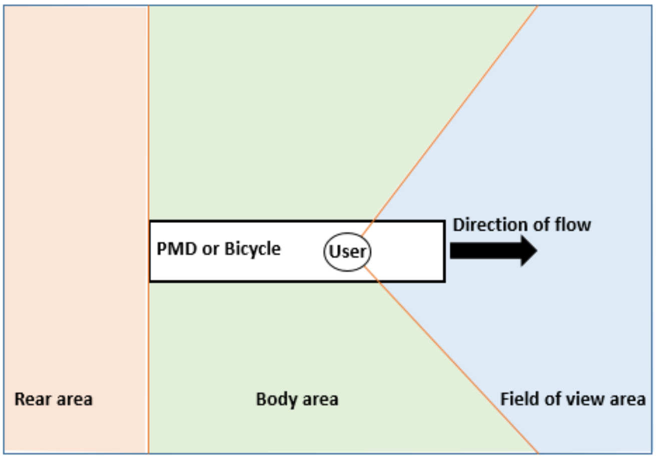

Figure 1: Area definition for the PMDs forces

The equations of each of the terms of SFM, including the formulations of f_i^{PMD} in each area definition, will be presented in the extended version of the paper.

Furthermore, as in SFM, the behavior of a road user is based on the forces applied on him/her, the dynamics of the vehicle itself are not explicitly considered. This simplification may not introduce bias when modeling pedestrian movements. However, bicycles and PMDs have inertia and additional constraints, especially in their lateral and turning movements. As a result, we consider vehicle dynamics based on the kinematic bicycle model proposed by (Polack, et al., 2017) to describe the maneuvers of bikes and e-scooters. The equations and assumptions used for the bicycles or PMDs maneuver will be presented in the extended version of the paper.

3. RESULTS AND DISCUSSION

For calibration, validation and verification, we used the database obtained by processing the videos of the experiment performed, containing the trajectories of each of road users type. In the present research, 50 % of the data has been used for calibration, 25 % for validation and 25% for verification.

The calibration method is an optimization function that consists in determining the parameters for which the error between the simulated trajectories and the experimental data trajectories is minimal. We have defined the error as the Root Mean Squared Error (RMSE), as shown below:

$$minimize\ g(\bar{x}) = \sqrt{\frac{1}{N_s N_n} \sum_t \left\| P_{obs}^t - P(\bar{x})_{sim}^t \right\|^2} \tag{4}$$

Where P_{obs}^t is the position observed of a road user type at time t, $P(\bar{x})_{sim}^t$ is the position obtained in the simulation for a road user type at time t, $\bar{x} = (x_1, x_2, \dots, x_m)$ are the calibration parameters of the model, N_s and $N_n$are respectively the number of step of objects and steps.

In order to minimize the equation 4 and determine the optimal model calibration parameters $\bar{x} = (x_1, x_2, \dots, x_m)$, the cross-entropy method proposed by (De Boer, et al., 2005) was used. The results and the interpretation of each of the obtained parameters will be explained in more detail in the extended paper.

The results show that the novel model can describe the interactions of different road users in shared spaces and it significantly reduces the error in the estimation of the lateral movements of PMDs.

4. CONCLUSIONS

This research proposes an extension of the Social Force Model proposed in (Helbing & Molnar, 1995; Moussaïd, et al., 2010; Yang, et al., 2018) to include the force applied by a PMD on different road users (pedestrian, bicycles and other PMDs). The novel model was calibrated, validated and verified through a database that has been generated by experimentation in a semi-controlled environment. The model can be used for urban planning purposes, traffic analyses, but also safety assessment as, once trajectories are obtained, the estimation of safety indicators (such as Time-to-Collision) is straightforward. We intend to include these aspects in our future works.

REFERENCES

Bozzi, A. D. & Aguilera, A., 2021. Shared E-Scooters: A Review of Uses, Health and Environmental Impacts, and Policy Implications of a New Micro-Mobility Service. *Sustainability,* Volume 13, p. 8676.

Christoforou, Z., Bortoli, A., Gioldasis, C. & Seidowsky, R., 2021. Who is using e-scooters and how? Evidence from Paris. *Transportation research part D: transport and environment,* Volume 92, p. 102708.

De Boer, P.-T., Kroese, D. P., Mannor, S. & Rubinstein, R. Y., 2005. A tutorial on the cross-entropy method. *Annals of operations research,* Volume 134, pp. 19-67.

Dias, C., Iryo-Asano, M., Nishiuchi, H. & Todoroki, T., 2018. Calibrating a social force based model for simulating personal mobility vehicles and pedestrian mixed traffic. *Simulation Modelling Practice and Theory,* Volume 87, pp. 395-411.

Helbing, D. & Molnar, P., 1995. Social force model for pedestrian dynamics. *Physical review E,* Volume 51, p. 4282.

Moussaïd, M. et al., 2010. The walking behaviour of pedestrian social groups and its impact on crowd dynamics. *PloS one,* Volume 5, p. e10047.

Polack, P., Altché, F., d'Andréa-Novel, B. & La Fortelle, A., 2017. *The kinematic bicycle model: A consistent model for planning feasible trajectories for autonomous vehicles?.* s.l., s.n., pp. 812-818.

Shah, N. R., Aryal, S., Wen, Y. & Cherry, C. R., 2021. Comparison of motor vehicle-involved e-scooter and bicycle crashes using standardized crash typology. *Journal of Safety Research,* Volume 77, pp. 217-228.

Valero, Y. et al., 2020. *Adaptation and calibration of a social force based model to study interactions between electric scooters and pedestrians.* s.l., s.n., pp. 1-7.

Yang, D., Özgüner, Ü. & Redmill, K., 2018. *Social force based microscopic modeling of vehicle-crowd interaction.* s.l., s.n., pp. 1537-1542.