Modelling pedestrian behavior through computational rationality under perceptual and motor constraints

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Abstract—**Understanding pedestrian behavior is essential for safe and socially compatible interaction in mixed traffic. Existing modelling approaches often face a tradeoff between interpretability and flexibility. Mechanistic models can explain behavior, but often rely on hand-crafted rules, while data-driven models can achieve strong predictive performance but may offer limited insight into the mechanisms underlying behavior. This work presents a computational rationality framework in which pedestrian behavior is modelled as boundedly optimal behavior under perceptual and motor constraints, with reinforcement learning used as an optimization method to derive policies.**

The framework is developed across three levels of pedestrian behavior. First, we model crossing decisions under noisy visual perception and looming-based cues. The model reproduces key empirical patterns in road crossing, including time-to-arrival dependent and speed-dependent gap acceptance, and suggests that some effects often described as biases can instead be understood as rational adaptation to perceptual uncertainty. Second, we incorporate motor constraints through a biomechanical account of walking effort and ballistic speed control, allowing the model to capture locomotor adjustment during crossing and explain walking speed patterns as an optimal tradeoff between time pressure and walking effort. Third, we extend the approach to a multi-agent setting in which the pedestrian and vehicle adapt to each other under visual and motor constraints. Using real-world interaction data, we show that the combined model produces more realistic interaction patterns. Overall, the work provides a unified framework that connects perception, action, and interaction for behaviorally realistic pedestrian modelling.

I. Introduction

Understanding and modelling pedestrian behavior is essential for safe and socially compatible interaction in mixed traffic environments [1]. Existing approaches to pedestrian behavior modelling are often divided into two broad classes. Mechanistic models provide interpretable accounts of decision making, but they often depend on hand-crafted rules and can be difficult to extend to richer interactive settings. Data-driven machine-learning models can achieve strong predictive performance, but they often offer limited interpretability and may fail to capture the mechanisms that generate human behavior. In this work, we present a computational rationality framework in which pedestrian behavior is modelled as boundedly optimal behavior under perceptual and motor constraints, with reinforcement learning used as an optimization method to derive policies rather than as a purely black-box predictor. This provides a middle ground between mechanistic and data-driven approaches by combining explicit modelling of human constraints with policies learned through optimization rather than hand-crafted behavioral rules. We develop the framework across three levels of pedestrian behavior: crossing decision, locomotor adjustment during crossing, and real-world pedestrian-vehicle interactions. Across these three levels, the aim is to show how increasingly realistic pedestrian behavior can emerge from a common computational framework rather than from separate task-specific models.

This work was supported by U.K. Engineering and Physical Sciences Research Council under Grant EP/S005056/1. (Corresponding author: Yueyang Wang.)

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Ethics Committee of the University of Leeds under Application No. 0536.

II. Crossing Decision Under Perception Constraints

First, we model crossing decisions under noisy visual perception and looming-based cues [2]. This model reproduces key empirical phenomena in pedestrian road crossing, including time-to-arrival (TTA)-dependent and speed-dependent gap acceptance, as well as kinematic effects in yielding scenarios. Importantly, the results suggest that some behaviors often described as biases, such as speed-dependent gap acceptance, can instead be understood as rational adaptation to perceptual uncertainty. This provides a mechanistic account of gap acceptance behavior while avoiding the need to assume such effects as fixed behavioral biases.

III. Locomotor Adjustment Under Motor Constraints

Second, we extend the framework to include motor constraints by integrating a biomechanical account of walking effort and ballistic speed control [3]. This allows the model to move beyond binary crossing decisions and capture locomotor adjustment during crossing in a richer task environment that includes yielding vehicles and external Human Machine Interface (eHMI) conditions. The results show that observed walking speed patterns can be explained as an optimal trade-off between time pressure and walking effort, highlighting the importance of modelling both perception and action in pedestrian behavior. These results show that realistic pedestrian modelling requires accounting not only for when pedestrians decide to cross, but also for how they physically regulate movement once crossing has begun.

IV. Multi-Agent Pedestrian-Vehicle Interaction

Third, we extend the approach to a multi-agent setting in which both pedestrian and vehicle are adaptive agents interacting under perceptual and motor constraints [4]. In this setting, visual constraints include not only perceptual uncertainty but also gaze-dependent acuity, allowing gaze behavior to emerge as part of the policy. Using real-world interaction data, we compare variants with and without visual and motor constraints. The combined model provides the most realistic interaction patterns, producing smoother speed adjustment, more human-like yielding behavior, and richer variability under uncertainty. These findings suggest that realistic pedestrian behavior modelling requires capturing not only how pedestrians make decisions, but also how their behavior develops through interaction with vehicles under perceptual and motor constraints. In particular, adding both visual and motor constraints improves not only average behavior but also the temporal smoothness and variability of interactions.

V. Conclusion

Overall, this work develops a unified computational rationality framework for modelling pedestrian behavior under perceptual and motor constraints. By embedding human-like uncertainty and action constraints directly into the reinforcement learning environment, the framework explains how behaviors such as gap acceptance, walking-speed adjustment, and pedestrian-vehicle co-adaptation can emerge as boundedly optimal responses rather than as scripted rules or black-box statistical relationships. The work therefore contributes not only a set of pedestrian models, but also a modular and generalizable modelling principle that connects perception, action, and interaction within a single framework. This makes it a promising starting point for behaviorally realistic pedestrian modelling in traffic, particularly for simulation-based research and for the development of more human-compatible autonomous systems. More broadly, the framework offers a basis for studying human road user behavior in a way that is both mechanistically interpretable and suitable for interactive simulation.

References

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