



GM3: A General Physical Model for Micro-Mobility Vehicles

Grace Cai*, Nithin Parepally*, Laura Zheng, Ming C. Lin
 Department of Computer Science, University of Maryland, College Park
 * Equal Contribution

Introduction

Micro-mobility vehicles (MMVs), such as bicycles, scooters, and skateboards, account for 133M+ US trips/year, yet remain poorly modeled.

The dominant Kinematic Bicycle Model (KBM) fails at high curvature; it ignores tire slip, load transfer, and lean, and can't generalize beyond single-track layouts. Existing simulators treat MMVs as "slow vehicles" or "fast pedestrians."

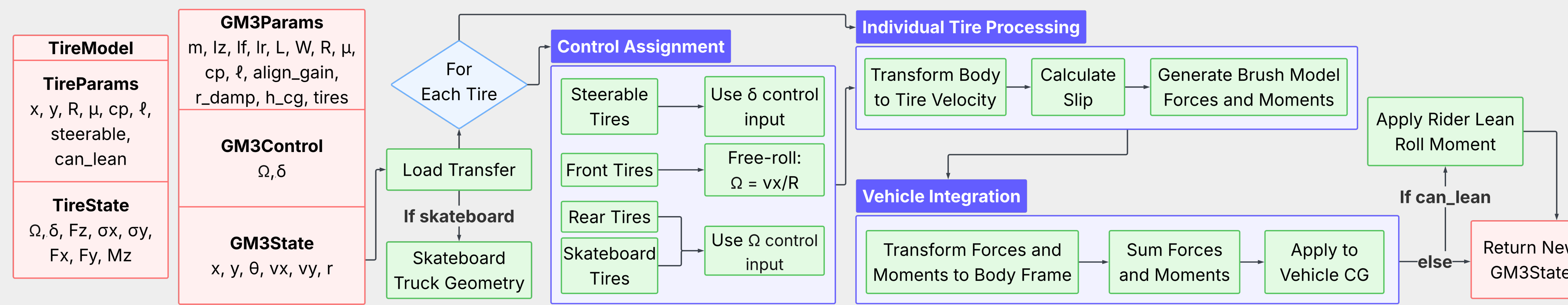
We introduce **GM3 (Generalized Micro-Mobility Model)**, a tire-level physical framework that captures slip, load transfer, rider/vehicle lean and supports arbitrary wheel layouts.

The primary motivation for this work is to enable future training and evaluation of autonomous systems in designing, prototyping, and testing environments where all types of micro-mobility agents move and interact realistically.

Methodology

GM3 State Update

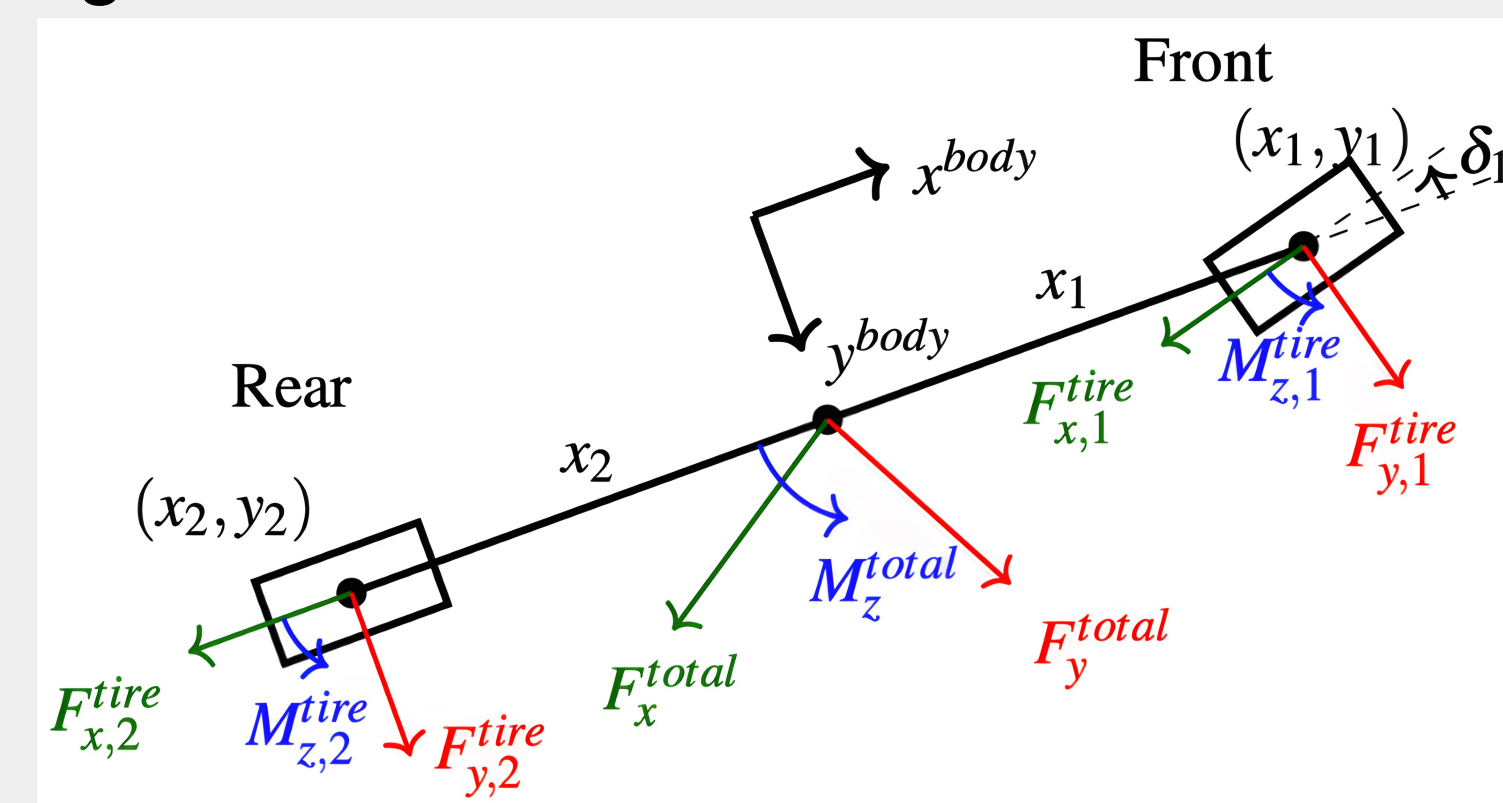
The state is updated through load transfer and skateboard truck geometry, control assignment for each tire, individual tire processing with the brush model, vehicle integration, and rider lean roll moment application.



Vehicle Integration

We apply the tire brush model to any tire configuration by:

1. Projecting body-frame velocity into tire frame
2. Computing brush model forces and moments
3. Transforming forces and moments back into body frame
4. Summing forces to obtain net acceleration



Load Transfer

Normal load is redistributed longitudinally then laterally across tires to reflect dynamic weight shift during acceleration and cornering.

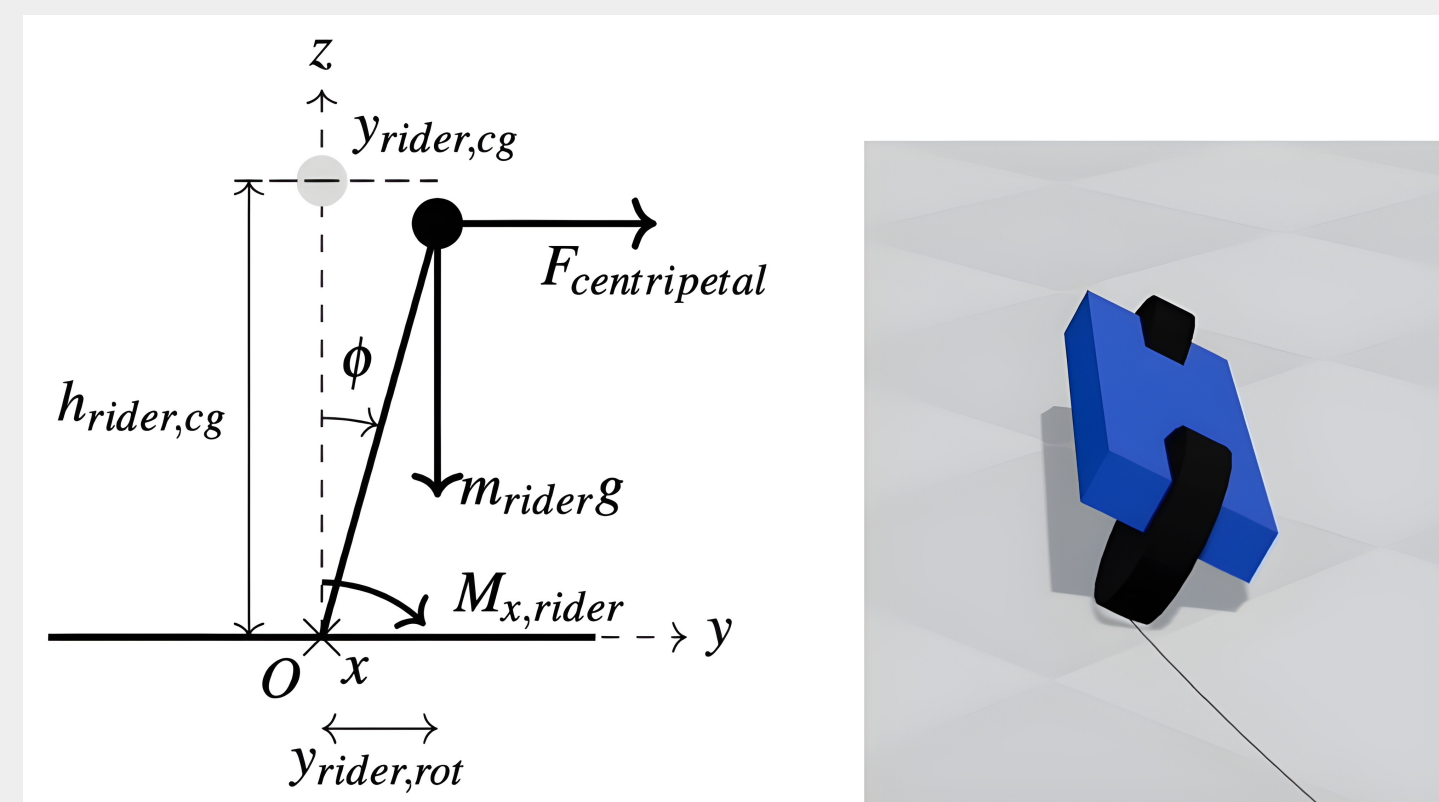
$$F_{z,front} = \frac{mgl_r}{n_f L} \quad F_{z,rear} = \frac{mgl_f}{n_r L}$$

$$T_{long} = \frac{ma_x h_{cg}}{L} \quad T_{lat} = \frac{ma_y h_{cg}}{W}$$

$$F_{z,i} = \begin{cases} F_{z,front} - \frac{T_{long}}{n_f} - T_{lat} \text{sgn}(v_i) x_i > 0 \\ F_{z,rear} + \frac{T_{long}}{n_r} - T_{lat} \text{sgn}(v_i) x_i \leq 0 \end{cases}$$

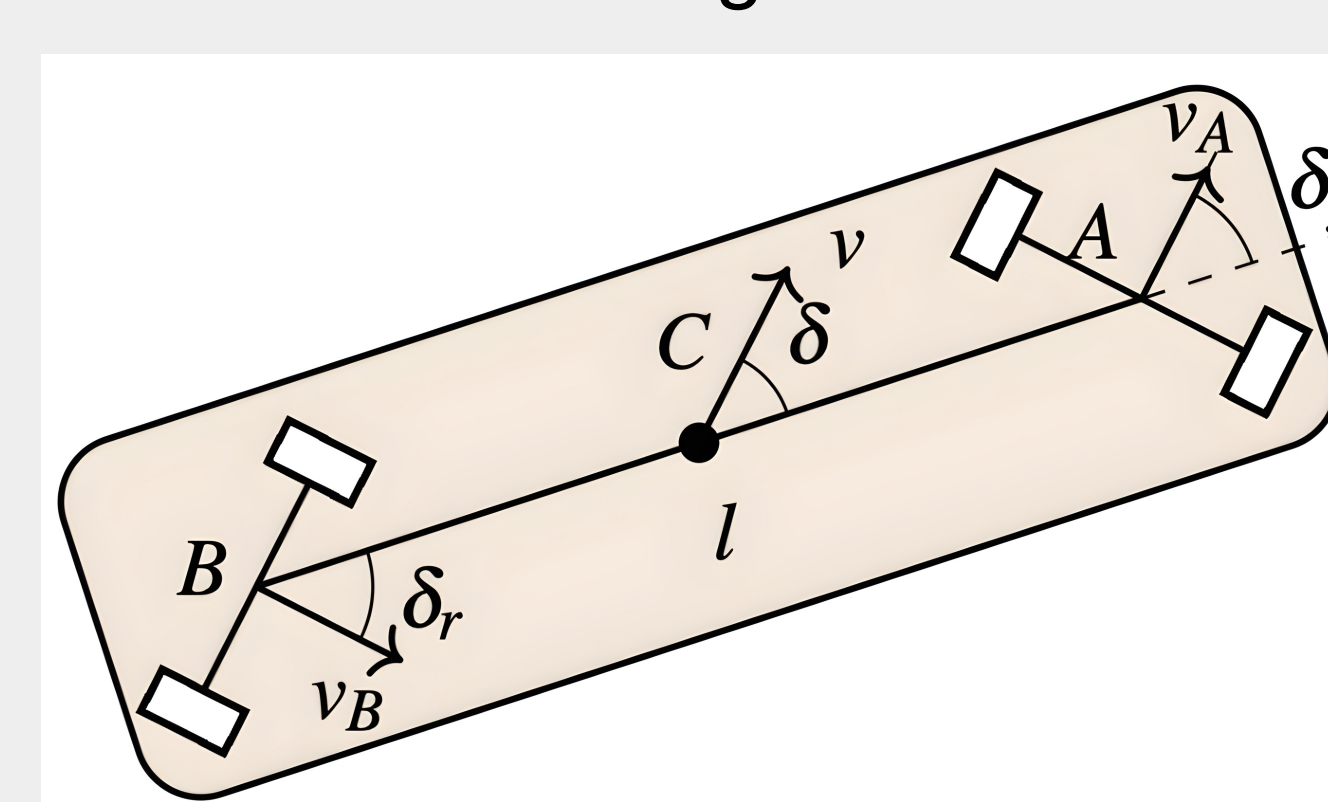
Lean

For lean-capable MMVs, rider lean angle is derived from velocity and turn radius. This angle is used to project the rider's gravitational force into the lateral axis and calculate the roll moment.



Skateboard Truck Geometry

Skateboards have two independent steering assemblies called "trucks" that rotate in opposite directions about a kingpin bolt when the rider leans to turn. We calculate these angles from the lean angle.



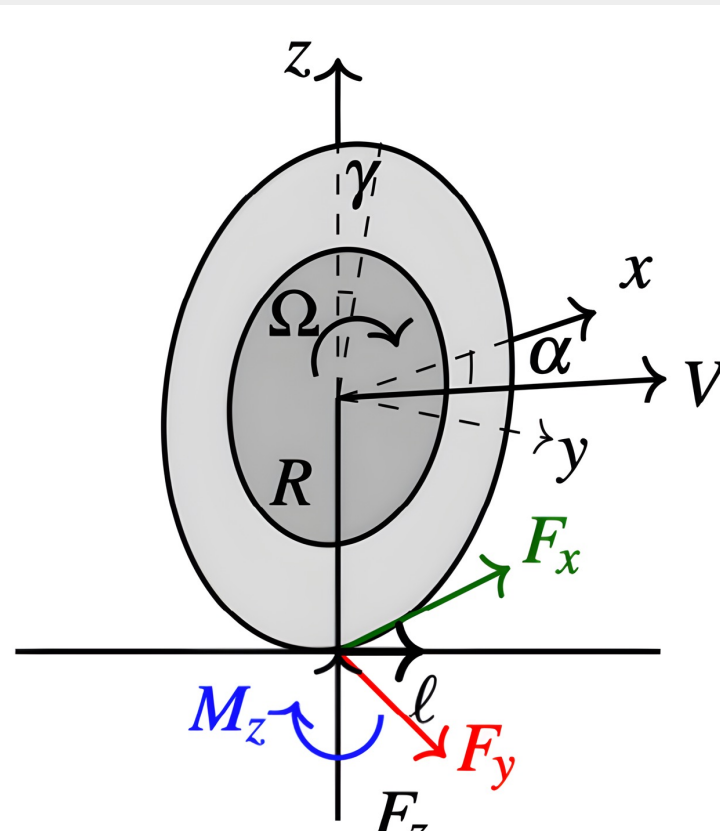
Tire Brush Model

The tire brush model represents the tire tread as a collection of independent and elastic bristles, each of which deflects under slip and friction forces. In GM3, this model serves as the foundation for capturing realistic MMV dynamics.

The tire brush model captures the non-linear transition from elastic deformation at low slip angles to sliding friction at high slip angles. This is important for modeling MMVs which experience significant slip since they

- are lightweight
- have small contact patches
- easily perform aggressive maneuvers

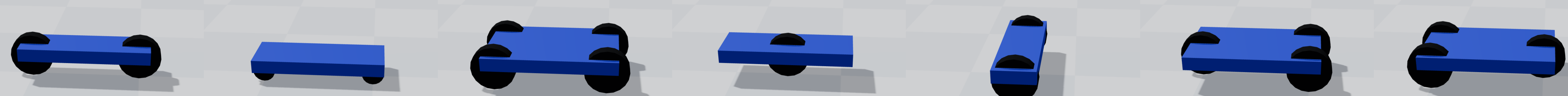
The model's relatively simple parameter set makes it practical for real-time control applications. Its physical basis allows for intuitive parameter tuning and provides meaningful insights into how tire design choices affect MMV dynamics.



Symbol	Description
ℓ	Half contact length
R	Tire radius
γ	Camber angle
μ	Coefficient of friction
c_p	Tread stiffness

Platform Diversity

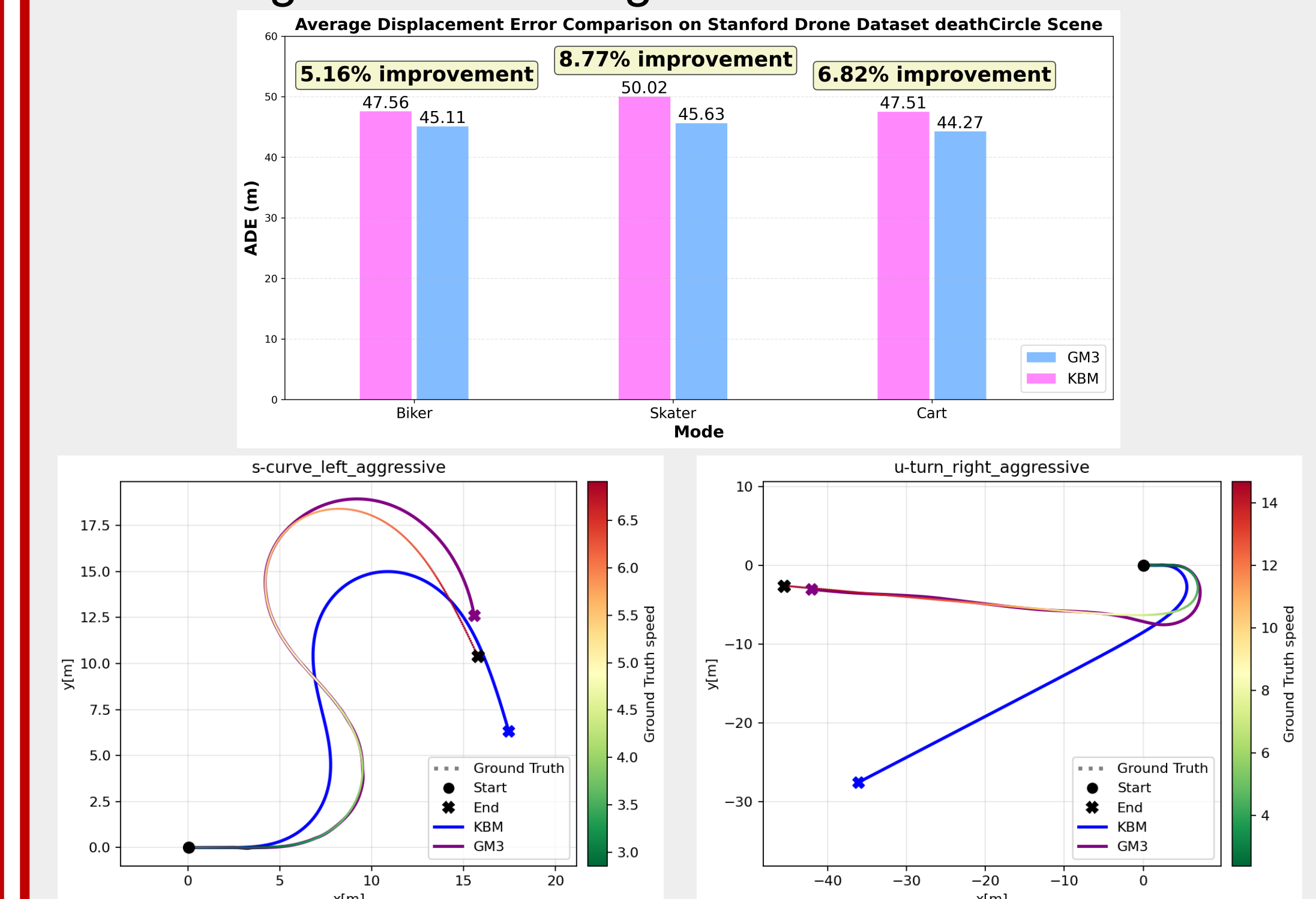
Currently, our model supports three control interfaces: explicit manual control, lean-to-steer with truck geometry, and differential drive. Since GM3 is modular, the control module can be extended to other control interfaces. This allows GM3 to support any wheeled MMV or robot, given individual wheel steering angles and angular velocity from the control module.



Experiments & Results

We evaluate GM3 against the Kinematic Bicycle Model (KBM). For real-world evaluation, we use trajectories from the Stanford Drone Dataset (SDD) deathCircle (roundabout) scene for three MMV modes (Biker, Skater, and Cart). To stress test GM3, we generate aggressive maneuvers, including S-curves and U-turns. We measure performance with Average Displacement Error (ADE) and Discrete Fréchet Distance (DFD).

Across the SDD trajectories, GM3 reduces ADE relative to KBM for all three modes. For DFD, GM3 improves over KBM on Skater and Cart, but performs worse on Biker due to lean-induced lateral biases. On the aggressive maneuver experiments, GM3 closely follows the ground truth while KBM tends to over/under steer in high-curvature segments.



Conclusion

GM3 demonstrates that a unified, tire-level physical model can better capture dynamics of MMVs than simplified kinematic models, especially in high-curvature segments and during aggressive maneuvers. This provides a stronger foundation for autonomous MMV stacks and mixed-autonomy traffic simulation.

Acknowledgments

This work is supported in part by Dr. Barry Mersky and Capital One E-Nnovte Endowed Professorships, University of Maryland Distinguished University Professorship, Maryland Transportation Institute Fellowship, National Science Foundation, and ARL-UMD ArtIAMAS Cooperative Agreement.

Project Website: gm3-sim.github.io/gm3

