Design and Retrofitting of Urban Intersections for Safe CAV Deployment: Enhancing VRU Interaction through Intersection Layout and Cooperative Perception

Master‘s Thesis of Benedikt Stern

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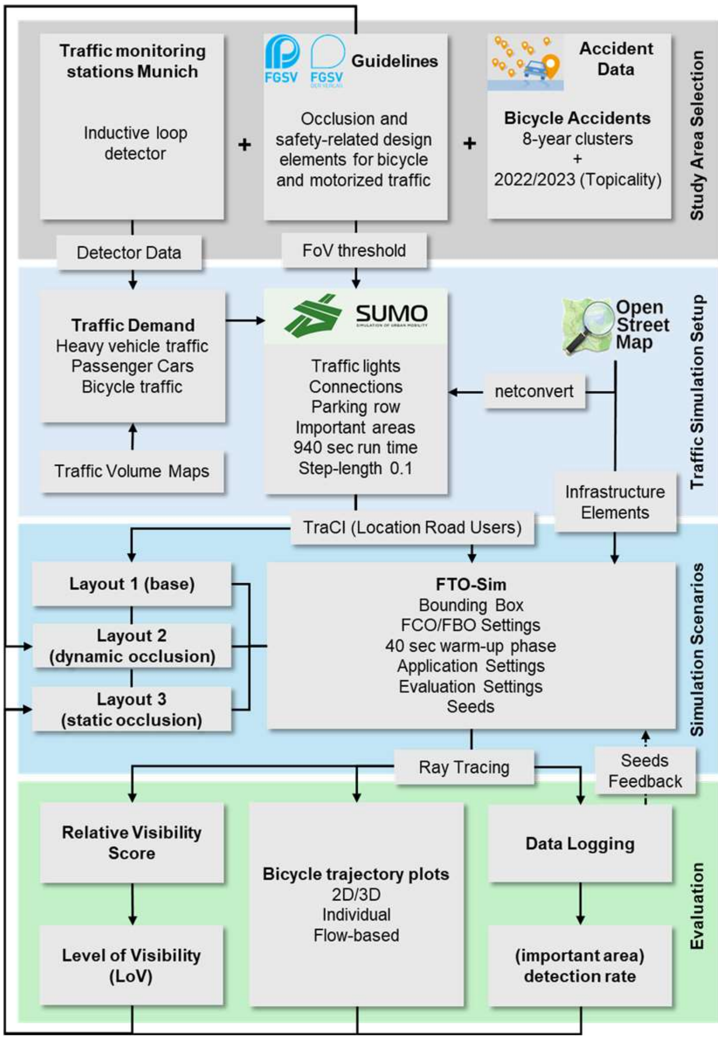
The emerging vehicle technology of Connected and Automated Vehicles (CAVs) offers significant potential to reduce the growing number of accidents involving Vulnerable Road Users (VRUs) by addressing critical causal factors, such as occlusion, through cooperative perception systems. However, the safe integration of CAVs into complex urban environments, particularly at intersections characterized by intricate geometries and high multimodal interaction density, demands detailed investigation and evidence-based design strategies.



This work examines the influence of urban intersection layout configurations on VRU safety in the context of CAV operation, with the objective of deriving practical recommendations to enhance interaction between CAVs and VRUs. A comprehensive classification of urban intersection design elements was first conducted based on applicable German technical regulations. Combined with a data-driven accident analysis, a real-world urban intersection with a high incidence of VRU-related accidents was selected as the basis for a detailed simulation study focused on cyclist visibility under varying CAV penetration rates.

Using the simulation framework for floating traffic observation (FTO-Sim), which integrates SUMO for traffic simulation and a Python-based ray tracing module for occlusion analysis, visibility simulations were conducted for the baseline layout and two regulation-informed modified configurations. Additionally, the Important Areas metric was introduced to evaluate zones of elevated conflict potential. The results indicated that the central intersection area, including the Important Areas, exhibited relatively high visibility even in the baseline layout. Measures targeting dynamic occlusion improved cyclist detection, albeit primarily at lower CAV penetration rates (≤ 30 %). The lane reduction measure, in particular, indicated substantial improvement in detection performance. Static occlusions were most pronounced along the intersection arms, primarily caused by infrastructure elements such as barriers, a parking row, bus shelters, and vegetation. Layout modifications to mitigate static occlusion, including converting two-way cycle paths to one-way facilities, removing sight-obstructing barriers, and relocating cycle paths to on-road lanes, yielded significant improvements in overall and Important Area visibility.

Layout	Scope	Measure	Metric	FCO target share [%] 10	20	30	40	50
Layout 2	Network-wide evaluation of measures	Reduction of dynamic occlusion	Overall					
			Important Areas		S			
	Evaluation of individual measures	Road diet	Overall					
			Important Areas					
		Reduction of turning lanes (f_39)	Overall					
			Important Areas					
		Reduction of turning lanes (f_44)	Overall					
			Important Areas					
Layout 3	Network-wide evaluation of measures	Reduction of static occlusion	Overall		S	S	S	S
			Important Areas					
	Evaluation of individual measures	Protected bike lane	Overall					
			Important Areas					
		One-way cycle path (f_39)	Overall	S	S	S	S	S
			Important Areas				S	S
		One-way cycle path (f_44)	Overall					
			Important Areas					
		Adjusted parking row alignment	Overall					
			Important Areas					
		Barrier removal	Overall					
			Important Areas		S			

Relative deviation of the bicycle detection rate of Layout 2 and Layout 3 compared to the baseline Layout 1: > 1 % / ≤ ±1 % / < -1 %

Significance (non-overlapping 95 % CI intervals): S

The findings suggest that passive design measures targeting static occlusion can provide robust and scalable safety enhancements for VRUs at urban intersections, even under higher levels of CAV integration. However, limitations include uncertainty in the quantification of individual design elements due to constrained simulation durations, highlighting the need for extended, empirically validated studies in further research.