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Emergent Behavior in Transportation Systems of Systems: A Model-Based Systems Engineering Case Study

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Abstract

Transportation networks are canonical examples of complex engineered Systems of Systems (SoS) in which independently useful constituent systems interact through shared infrastructure and information. This paper presents a case study showing how emergent behavior in transportation SoS can be modeled, detected, and analyzed using model-based systems engineering (MBSE) and agent-based simulation. Three scenarios are examined: a freeway–arterial corridor with routing feedback, a decentralized signalized grid, and a microscopic car-following model that reproduces phantom traffic jams. System-level metrics—including mean speed, queue accumulation, spillback frequency, and speed variance—are used to detect regime changes automatically. The results show that interaction structure rather than component malfunction is the main driver of congestion cascades, distributed network breakdown, and stop-and-go waves. Annotated figures and traceable algorithms are used to connect architecture, simulation, and validation evidence. The study contributes a reproducible framework for reasoning about emergence in transportation and other socio-technical SoS, and it demonstrates how engineering interventions such as route-throttling and demand smoothing can improve resilience while preserving local autonomy.

Keywords
System of Systems, Emergent Behavior, Transportation Systems, Agent-Based Modeling, Model-Based Systems Engineering

Biographies
Mustafa Chmeiseh is a Staff Connectivity Standards Engineer at General Motors and a PhD candidate in Systems Engineering at Oakland University. He specializes in automotive connectivity, systems architecture, and emergent interactions in cyber-physical systems. His recent work focuses on transportation and vehicle systems-of-systems, digital key ecosystems, and model-based engineering for complex standards-driven platforms. He holds graduate and undergraduate degrees in engineering and computer science and is a licensed Professional Engineer. His research interests include emergent behavior, agent-based simulation, systems-of-systems assurance, and the interaction between connectivity, autonomy, and smart infrastructure.

Sankar Sengupta is a Professor in the Industrial and Systems Engineering Department at Oakland University. He teaches production systems, workflow analysis, computer simulation, manufacturing processes, and quality. His research addresses modeling and performance analysis of manufacturing and service systems, including simulation-

based methods for design and control. In this paper, he contributes academic supervision and systems-engineering perspective for the transportation case study.