Stress-testing Traffic Signal Control System
through Synchronous Digital Twin Simulation

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TransModeler
Traffic Simulation Software

MOTIVATION

- Modern signal systems depend on:
  - Firmware-driven controllers
- Failures arise from:
  - Control logic faults
  - Data input errors, or
  - Corner cases that surface only after long runtime
- Need a *systematic* way to test resilience
- Digital twins enable *risk-free* experimentation with *real* controller logic

OBJECTIVE

- Develop
  - Digital Twin-based resilience testing framework for signal systems
- Integrate
  - Real controller firmware/hardware into microsimulation
- Enable
  - Systematic way to signal system’s resilience
- Quantify
  - Performance and scalability

TRAFFIC SIGNAL CONTROLLERS OVERVIEW

HARDWARE, SOFTWARE AND COMMUNICATION PROTOCOLS

	NEMA Controller	**2070 Controller**	**ATC**
Developer	NEMA	Caltrans (active) ITE ATC Joint Committee	ITE/ASSHTO/NEMA
Latest Version	NEMA TS-2 2021 v3.08 (Nov 2021)	Caltrans TEES 2020 (Nov 2020) ATC 5202 v3.94 (Dec 2012) rescinded	ATC 5201 v06A (July, 2020)
Signal Control Functions Definition	Pretimed (Interval-based) Control Actuated Control Actuated Coordination Time-based Preemption Malfunction Management	None	None
Hardware Specification	CU dimensions, BIUs, TFs Auxiliary Devices (LSW, Flashers, Flash Transfer Relays and Loops)	Strict Modular Hardware Specification	Modular Hardware Specification
Software Specification	Does not specify OS	Linux Kernel 2.6.35+ OS-9 4.02+	Linux Kernel 2.6.35+
Primary In-cabinet Serial Communication Standard	SDLC at 153.6Kbps	SDLC at 153.6Kbps	SDLC/HDLC at 614.4Kbps
NTCIP 1202 Supported	Yes	Yes	Yes

Table 1: Summary of NEMA, 2070 and ATC Controllers and Communications

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DIGITAL TWIN

WHAT, WHY, AND HOW

- Interface indistinguishability (the “Turing” test)
- Controller interface through I/O protocols
  - NTCIP 1202 objects
  - SDLC/HDLC serial frames
  - Specialized performance-oriented protocol
- Microscopic traffic simulator, running
  - In real-time x1 speed factor, or
  - Faster-than-real-time x30 ~x100 speed factor
- Together, the most realistic traffic signal controller logic

PROTOCOLS

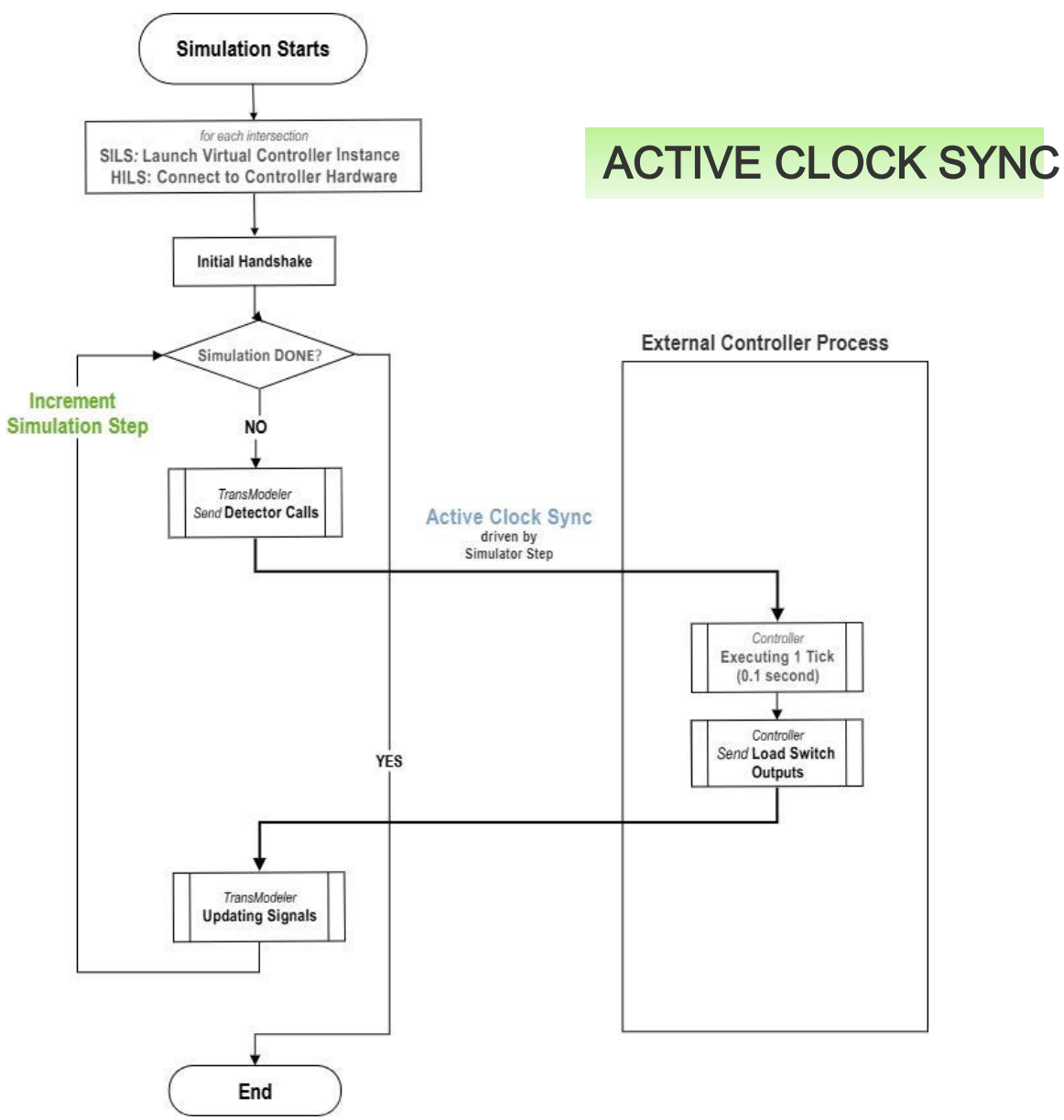
PERFORMANCE AND SCALABILITY – SYNC MODE AND COMMUNICATON PROTOCOLS

	NTCIP	**SDLC**	**Proprietary**
HILS	Support	Support	Support
SILS	Support	-	Support
Clock Sync Model	Passive	Passive	Passive and Active
Simulation Speedup	x1 Realtime	1x Realtime	As fast as the simulator speed
Packet Overhead	High (extra bytes for sequence, OID, community, PDU, error status, error index, variable bindings), easily exceeding 40 bytes	Relatively low (just 6 bytes: opening flag, address, control, CRC and closing flag)	Very low due to very "thin" packet design
Pros	- Open/public domain standard - Straightforward to implement - Can be both software or hardware based	- Open/public domain standard - Hardware-focused simulation testing	- Accelerated sim testing - AI training and ATSPM - Sim-based predictive analytics - Scalable for large network
Cons	- Limited to 1x real-time - Not scalable for accelerated simulation testing - Clock synchronization accuracy	- Limited to 1x real-time - Not scalable for accelerated sim testing - Clock synchronization accuracy - Not scalable for large-network sim	- Proprietary protocol and API

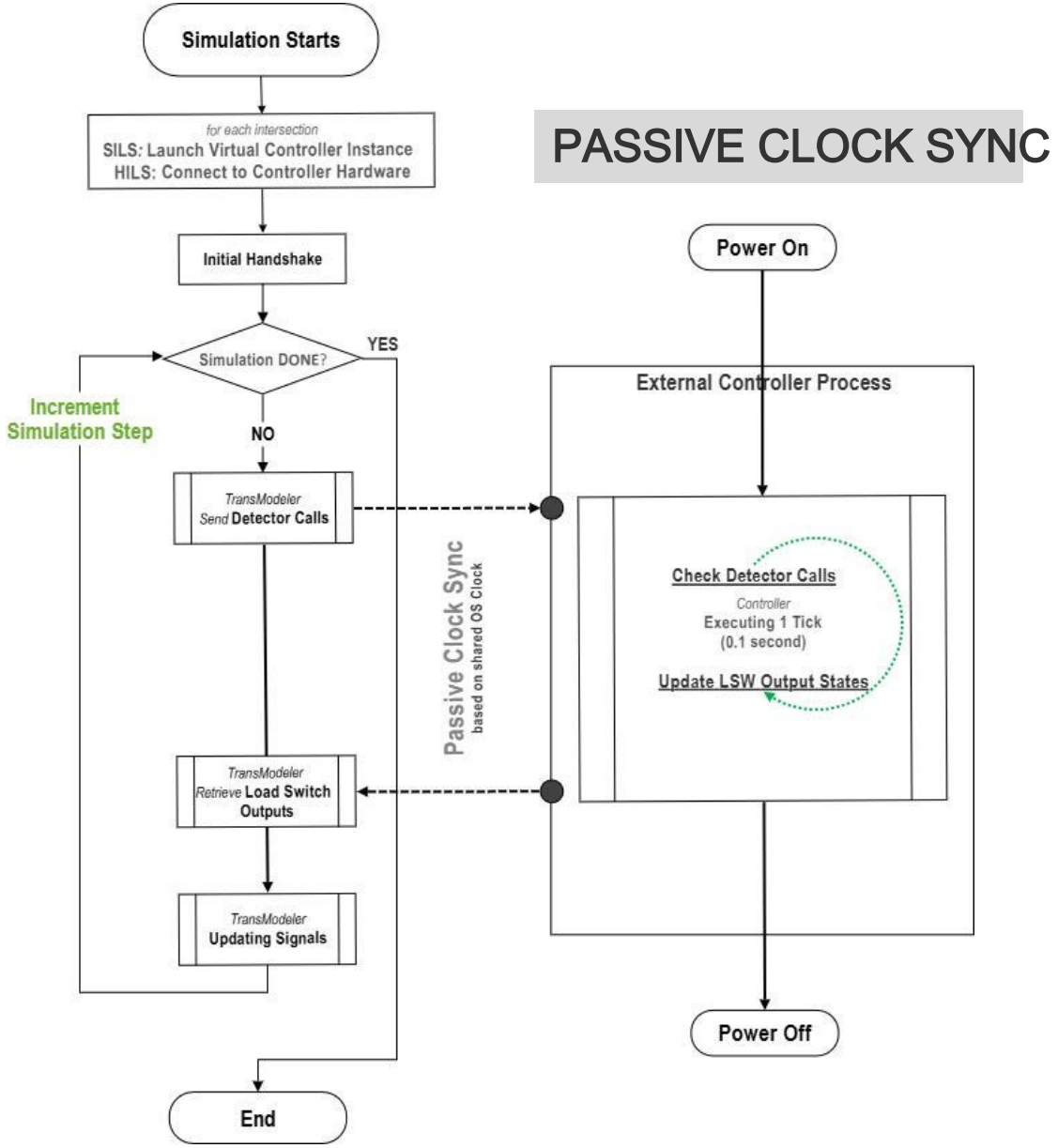
Table 2: X-in-the-Loop Simulation and Communication Protocols

SYNCHRONIZATION ARCHITECTURE

TRANSMODELER – ARCHITECTURAL MODELS



ACTIVE CLOCK SYNC

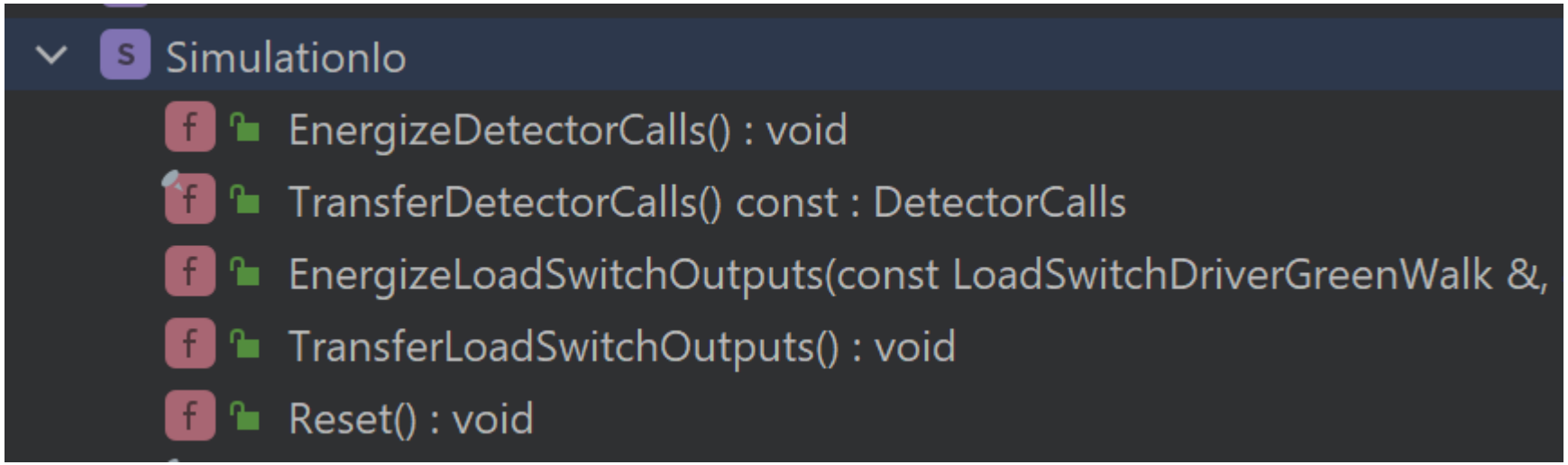


PASSIVE CLOCK SYNC

CLOSE-TO-HARDWARE SEMANTICS

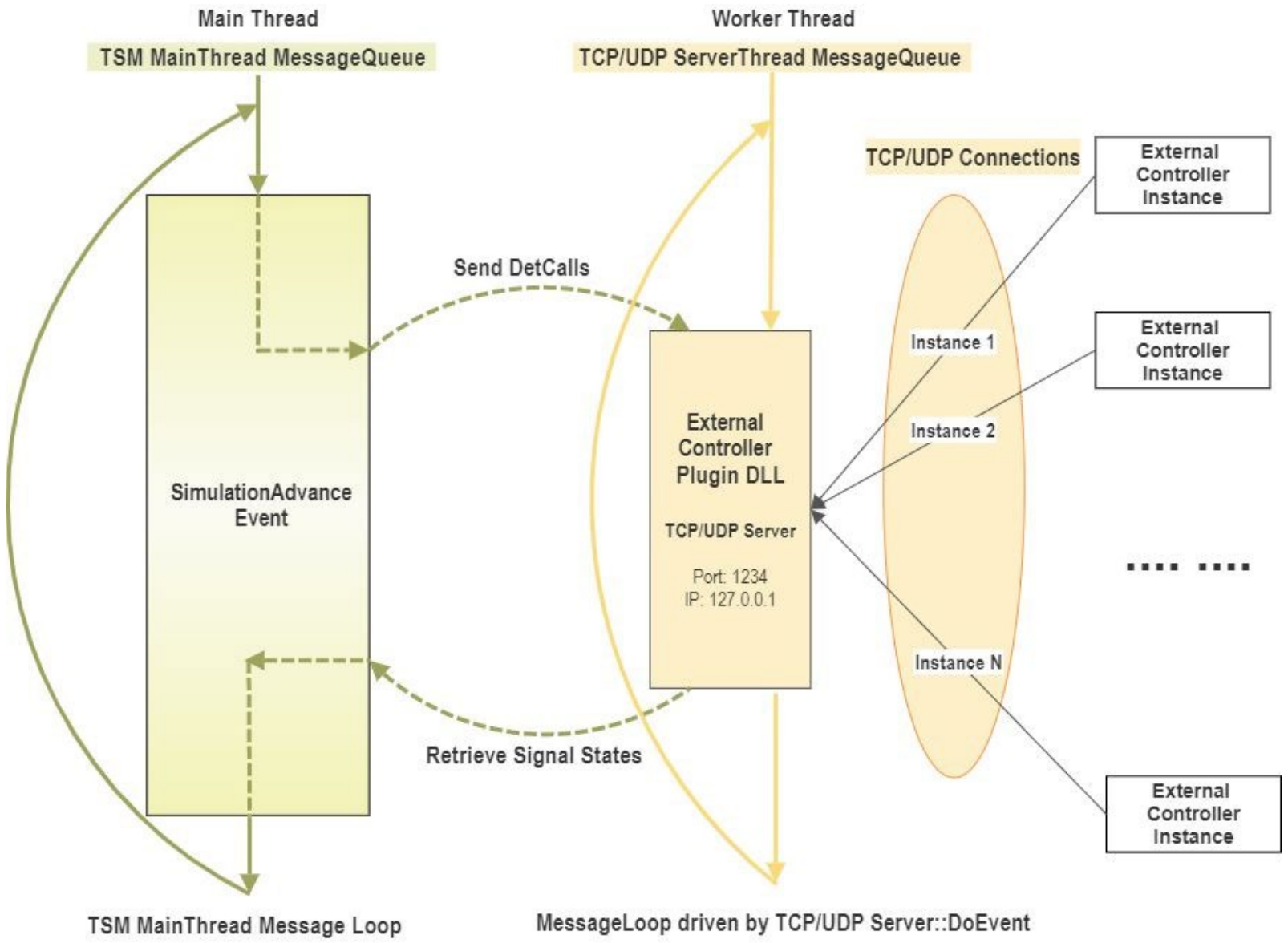
TRANSMODELER – SEMANTIC I/O EMULATION

NEMA TS-2 command frame shall be transferred to the BIU output pins upon receipt of Type 18 Frame (Output Transfer Frame).



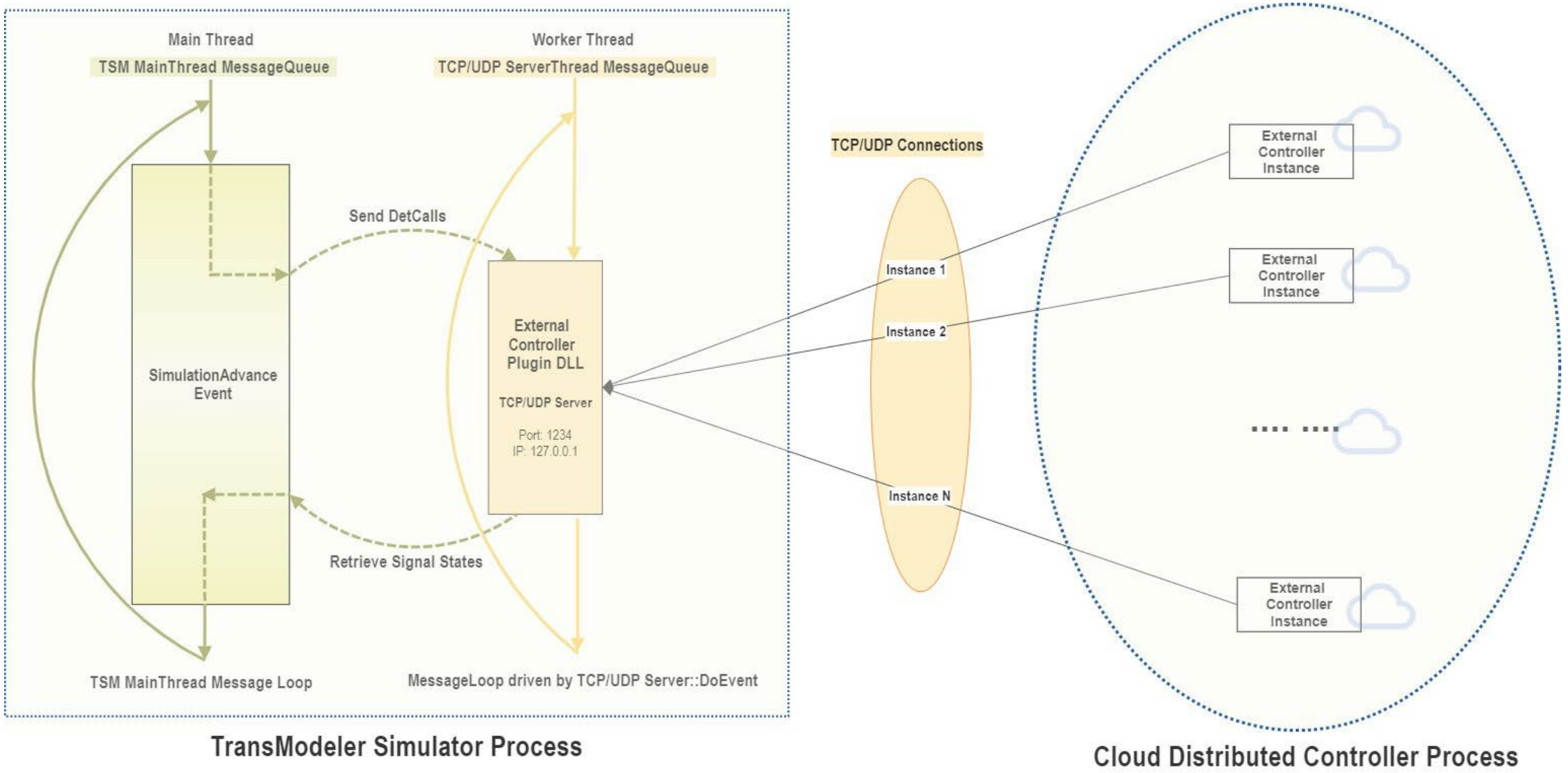
THREADING AND DISTRIBUTION

TRANSMODELER – THREADING MODEL



SERVER FARM: CONTROLLER AS A SERVICE

TRANSMODELER – THREADING MODEL



SPEED UP UPPER BOUND EQUATION

QUANTIFY THE MAXIMUM POSSIBLE XILS SPEEDUP

XILS Runtime Speed Up

$$\text{Speed-up} = \frac{100ms}{T_{\text{controller}} + T_{\text{comm}} + T_{\text{sim}}}$$

- Quantifies maximum achievable acceleration
- Local Deployment (MAXTIME): sub-linear scalability
- On-premise cloud (Omni eX): near const O(1) scalability

TESTING – MAXTIME INTEGRATION

PERFORMANCE AND SCALABILITY OF LOCAL DEPLOYMENT

- Q-Free MAXTIME is a local Windows desktop software package: sub-linear scalability
- Average per-tick process time + local communication delay: 1 ms - 1.5ms
- For an arterial with 23 intersections, what would be the upper bound of the simulation speedup?

TESTING – MAXTIME INTEGRATION

PERFORMANCE AND SCALABILITY OF LOCAL DEPLOYMENT

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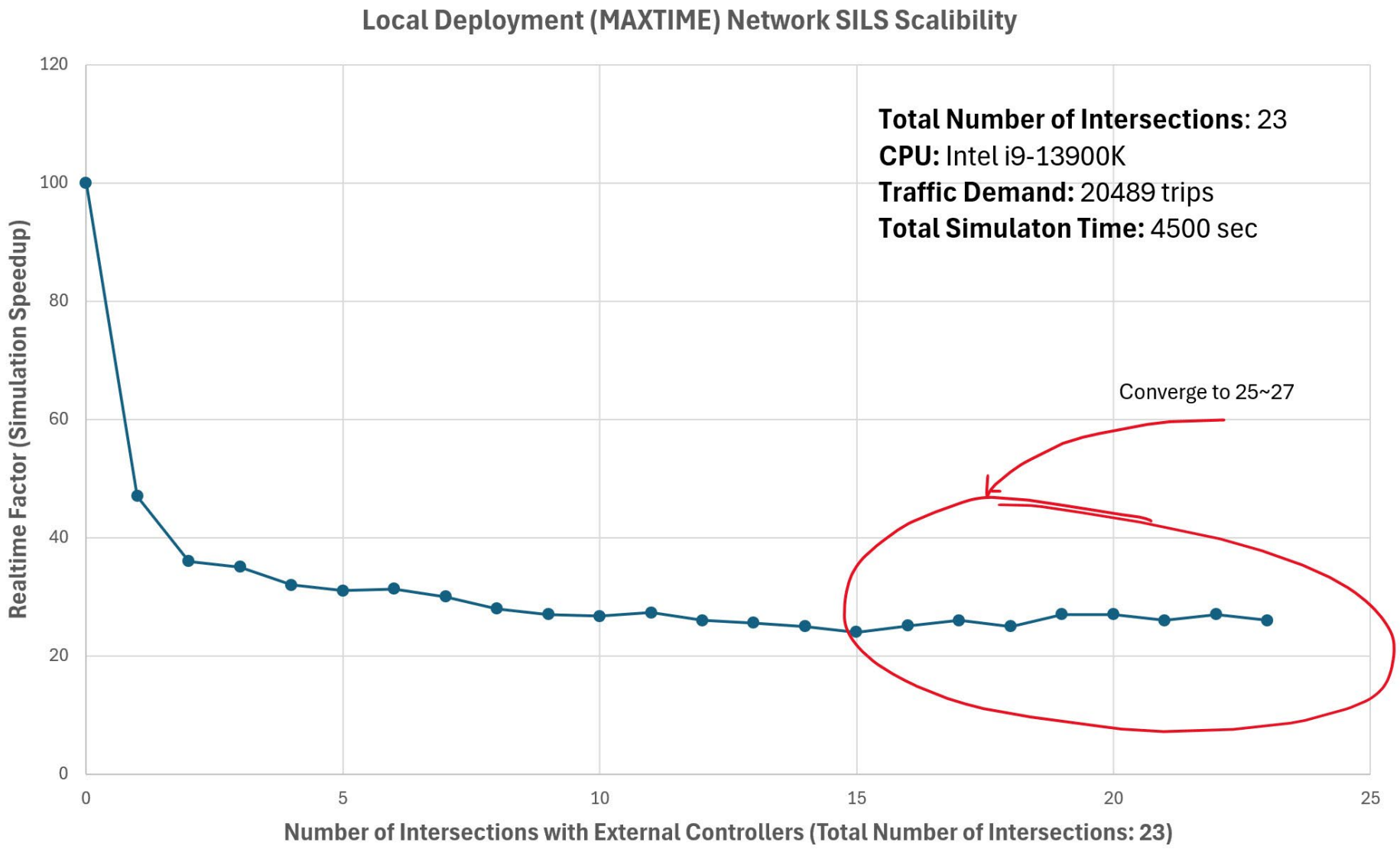
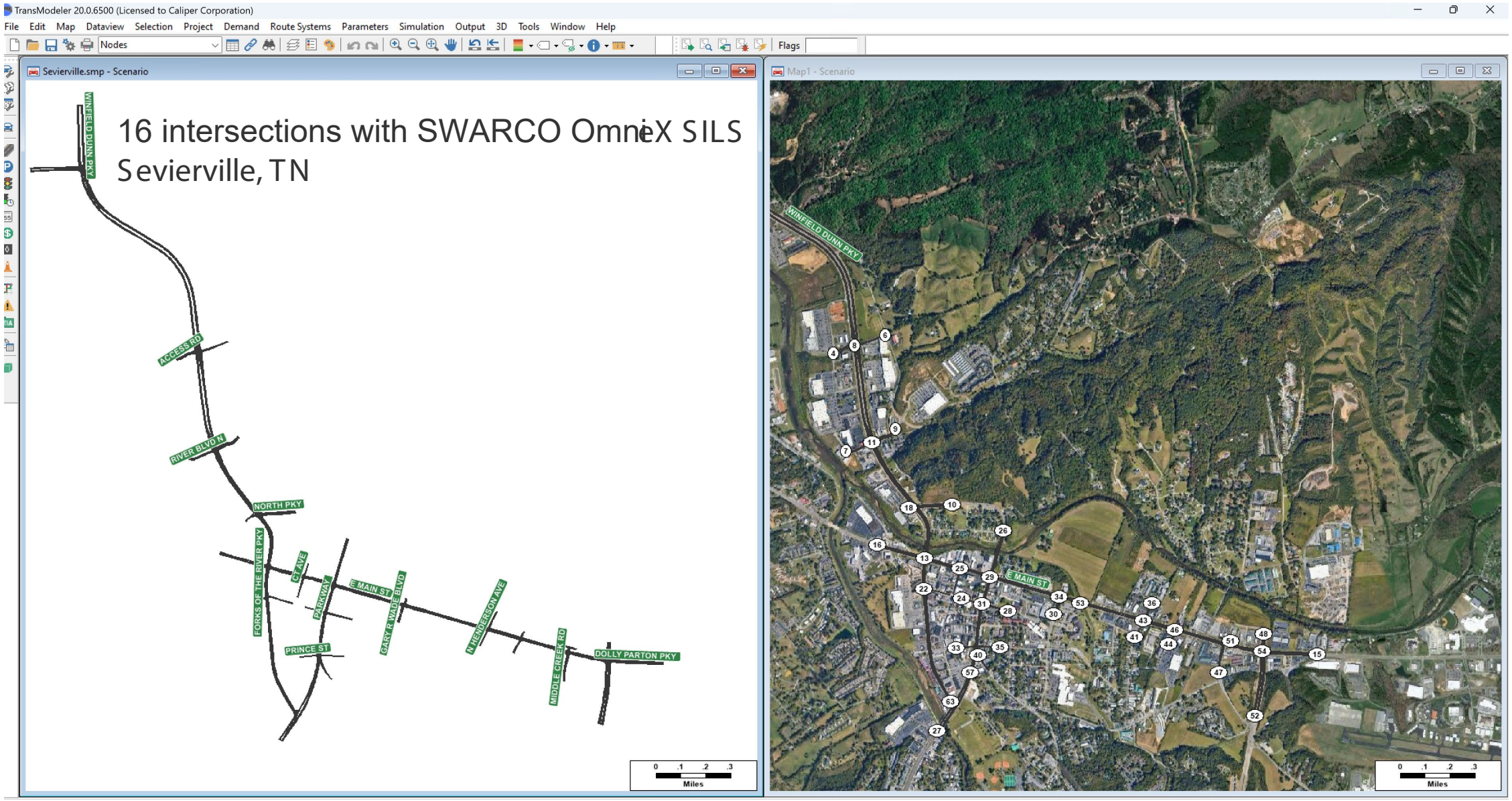


TESTING – OMNI EX INTEGRATION

PERFORMANCE AND SCALABILITY OF CLOUD DEPLOYMENT



TESTING – OMNI EX INTEGRATION

PERFORMANCE AND SCALABILITY OF CLOUD DEPLOYMENT

- Omni eX software deployed in cloud as virtual controllers: near const O(1) scalability
- Average per-tick process time + local communication delay: 12-15 ms (cloud physically close to Boston)
- For an arterial with 16 intersections, what would be the upper bound of the simulation speedup?

APPLICATIONS

- Signal Optimizations and Benchmarking
  - Signal Timing Plan Design, & adaptive signals
- System Fine Tuning
  - Offset/Transition Logic/Overlap Testing
- Training and Education
  - Classroom, or Professional
- AI integration via LLM Tooling/MCP protocol
  - On-going work, making signal operations interpretable by AI
- Traffic Signal Systems Cybersecurity
  - SDLC/NTCIP (w/ the intro of SNMPv3)
  - Operations Level

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Q&A

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TransModeler®
Traffic Simulation Software