Using STAMP for the Modeling and Control Of Autonomous Vehicle Fleets at Intersections During Infrastructure Failures and Other Edge Cases

Updates to ISO 26262, ASPICE, SOTIF, ISO 21434

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Agenda

Introduction

- On December 22, 2025, a power blackout and wireless communication disruption in San Francisco caused a fleet of Waymo robotaxis to stand still, blocking traffic at multiple intersections
- This is not an isolated incident — AV fleets are increasingly vulnerable to infrastructure service failures
- The problem: how do we model, monitor, and control AV fleets at city intersections when the underlying infrastructure fails?
- Focus areas: traffic congestion, availability, and performance — not just safety

Problem Definition & Assumptions

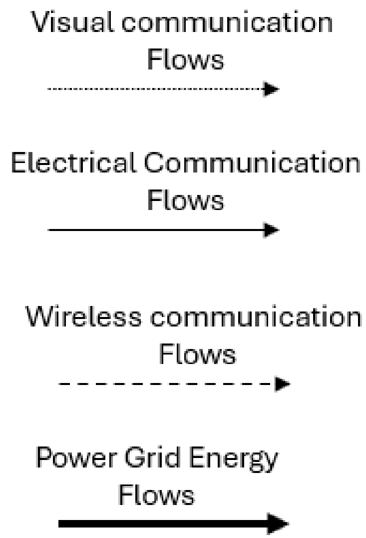
- AV fleets operate without human safety drivers or remote drivers; remote operators provide supervisory support only
- Fleet vehicles rely on wireless communications for remote operator interaction
- Traffic lights at intersections depend on the power grid
- AVs obey traffic laws but cannot control non-fleet vehicles or pedestrians
- Key challenge: infrastructure failures (power outages, wireless disruptions) combined with unpredictable human behavior create severe intersection congestion
- Research goal: develop models, policies, rules, and protocols to mitigate congestion under these conditions

Stakeholders & Actors

- A rich, multidisciplinary set of actors is involved:
  - **Vehicle layer**: Autonomous vehicles (AV), ego vehicle (EV), fleet vehicles (FV), other vehicles (OV)
  - **Operations layer**: Fleet operator (FO), remote operators (RO)
  - **Infrastructure layer**: Power grid (EG), wireless communications, traffic lights (TL)
  - **Environment layer**: Pedestrians, city intersection, emergency responders
  - **Governance layer**: City government, transport regulators, general public
- V2X communications (V2FO, V2RO, V2V, V2I, V2P) connect these layers

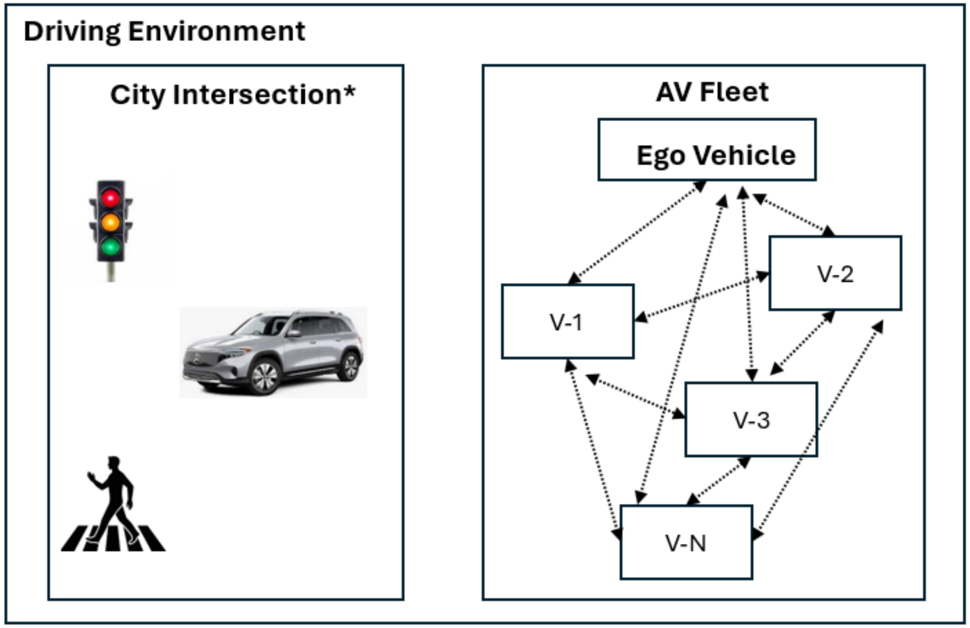
STAMP Framework Extensions

- Standard STAMP was designed primarily for safety analysis; this work extends it in two important ways:
- **Extension 1 — Performance & Availability**: STPA is adapted to address traffic congestion, fleet efficiency, and service availability, introducing *Inadequate Control Actions (ICAs)* alongside the standard Unsafe Control Actions (UCAs)
- **Extension 2 — Visual Monitoring as a Formal Feedback Channel**: Standard STAMP feedback is implicitly sensor/electronic-based; this work formally models visual monitoring — both direct (AV onboard cameras) and remote (operators viewing camera feeds) — as a distinct and explicit feedback channel
- The control structure distinguishes four communication flow types: visual, wireless, electrical, and power grid



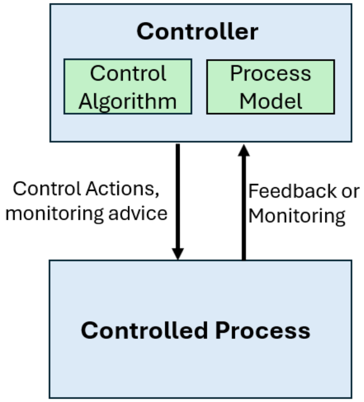
Control & Monitoring Model

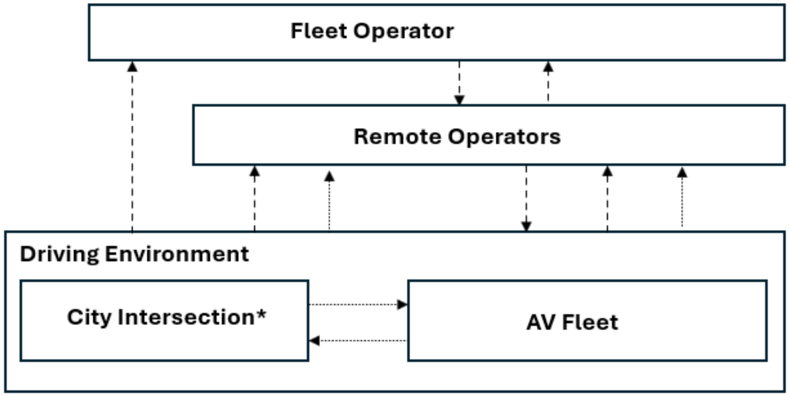
- The driving environment is decomposed into two parts:
  - ***City Intersection**** — traffic lights, non-fleet vehicles, pedestrians; these elements can only be *monitored*, not controlled
  - ***AV Fleet*** — ego vehicle plus N fleet vehicles; these are the controllable elements



Control & Monitoring Model

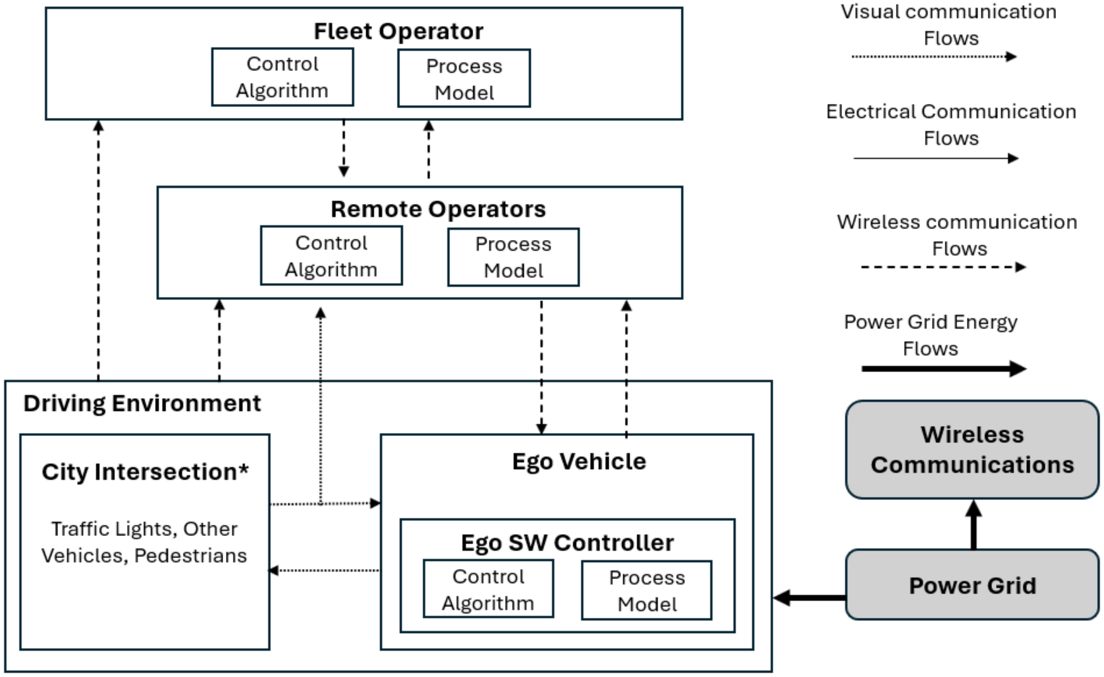
- Underlying basic STAMP control structure is used
  - In a supervisory and hierarchical fashion
- Supervisory control flow: **Fleet Operator → Remote Operators → AV Fleet**
- Control is performed exclusively via wireless communication
- Monitoring is performed wirelessly, visually, or a combination of both
- Remote operators can achieve visual awareness of the intersection through AV onboard camera feeds transmitted wirelessly





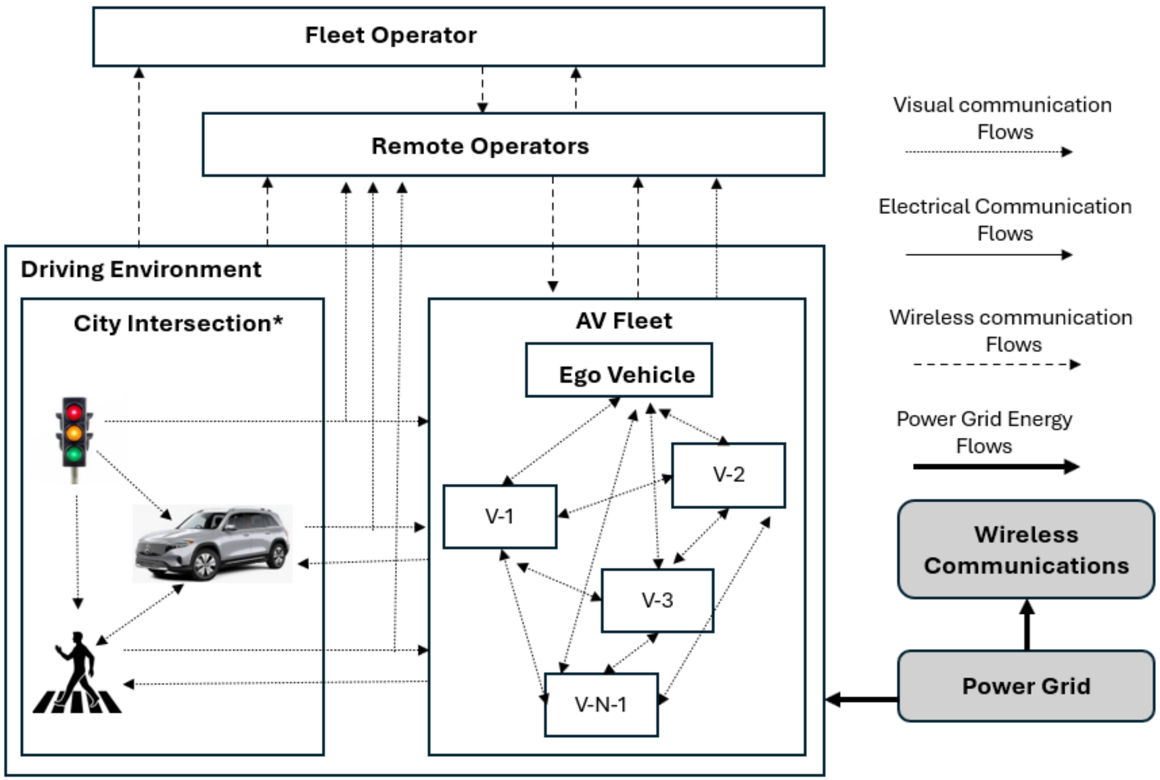
STPA Control Structures

- Two control structure cases are modeled:
  - **Case 1 — Ego Vehicle**: A single AV controlled by one remote operator, who is in turn directed by the fleet operator; the ego vehicle SW controller interacts with the city intersection* and depends on wireless communications and the power grid



STPA Control Structures

- **Case 2 – AV Fleet**: A distributed system of N vehicles and M remote operators; vehicles communicate with each other and with operators through a wireless network; fleet-level concerted control is possible



STPA Results: UCAs, ICAs & Loss Scenarios

- **Losses**: Intersection congestion (L-1), blocking emergency responders (L-2), crashes (L-3), hitting pedestrians (L-4)
- **System Constraints**: Reliability and latency of power grid, wireless communications, remote operator visual monitoring, and ego vehicle perception must all be acceptable
- **Unsafe Control Actions (UCAs)**:
  - UCA-1: Timid driving behavior of the ego controller
  - UCA-2: Remote operator issues incorrect monitoring advice (e.g., reports green light when it is red)

STPA Results: UCAs, ICAs & Loss Scenarios

- **Inadequate Control Actions (ICAs)**:
    - ICA-1/2/3: Remote operator issues incorrect advice regarding status, nature, or location of vehicles at the intersection
- **Key Loss Scenarios** (selected): Power grid outage (S-6), wireless communication outage (S-7), high communication latency (S-8), remote operator overload (S-1), reckless non-fleet drivers (S-10), immobilized vehicles (S-12)

Control Action Requirements & Distributed Protocols

- Control actions must satisfy the following requirements:
  - **Proactiveness** — anticipate failure conditions before they escalate
  - **Robustness** — handle surges in communication load and operator unavailability
  - **Resiliency** — have fallback rules when expected responses do not arrive
  - **Cautiousness** — avoid actions that could worsen congestion or create safety hazards
  - **Distributed** — congestion reduction is a concerted effort across all fleet vehicles, not just a single ego vehicle
- Distributed control protocols are envisioned as a key mechanism, with the fleet collectively negotiating intersection behavior under degraded conditions

Summary & Conclusions

- STAMP is applied to a novel, real-world problem: AV fleet management at intersections under infrastructure failures
- Two meaningful extensions to the STAMP framework are introduced: adaptation for performance/availability and formal visual monitoring modeling
- The *City Intersection** abstraction cleanly separates controllable from uncontrollable elements

Thank You!

Questions?

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