

From Standards to Systems

What the TSN ecosystem still owes industry

SILVIU S. CRACIUNAS

SENIOR PRINCIPAL SCIENTIST, NXP

ASSOCIATE PROFESSOR, TECHNICAL UNIVERSITY OF DENMARK



EMSOFT Special Session:

Making Time-Sensitive Networking Deployable:
A Comprehensive Lifecycle Architecture



After 10 years of standardization, deployment is still the bottleneck



- I – SELECTION**
Which mechanism, or combination of mechanisms, satisfies application requirements?
- II – PARAMETERIZATION**
Which parameter values should be assigned, and how to derive them?
- III – VERIFICATION**
How is the resulting configuration verified?

ENGINEERING DECISION	 IEC/IEEE 60802	 IEEE 802.1DG
Traffic types and timing requirements	◐	◐
Synchronization accuracy and error budgets	●	○
Mandatory device feature set (conformance)	●	●
Mechanism selection per traffic type	◐	◐
Shaper and schedule parameter values	○	◐
Configuration model and synthesis toolchain	◐	○
Runtime reconfiguration	◐	○
End-to-end configuration verification	○	○

● resolved normatively

◐ partial or informative only

○ open or explicitly delegated

Shaping profiles

The two profiles mandate near-disjoint mechanism sets



IEC/IEEE 60802 : 2026

TAS required at 100 Mbit/s and 1 Gbit/s

FP required — unconditionally for bridges,
conditionally for end stations

ATS — not referenced in the document



IEEE 802.1DG : 2025

ATS & CBS mandatory,
on the 2 highest traffic classes

Ingress policing mandatory

TAS and FP optional; FRER not used;
synchronization only recommended



Domain differences alone do not fully explain this divergence.

Leaving TAS as optional institutionalizes ATS/CBS for automotive.

Shaping profiles

The two profiles mandate near-disjoint mechanism sets



IEC/IEEE 60802 : 2026



IEEE 802.1DG : 2025

An early design rationale behind automotive TSN assumed independently developed domains that exchange rate contracts without a common clock¹.

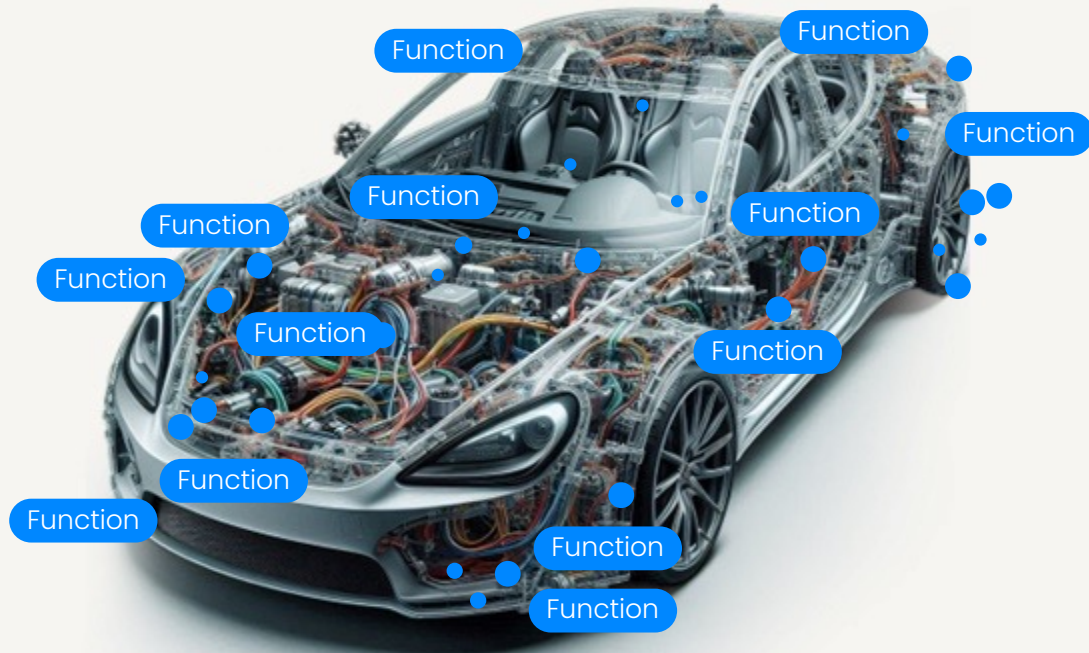
¹ <https://www.ieee802.org/1/files/public/docs2014/new-tsn-specht-ubs-automotive-1114-v01.pdf>

Domain differences alone do not fully explain this divergence.

Leaving TAS as optional institutionalizes ATS/CBS for automotive.

Vehicle transformation underway

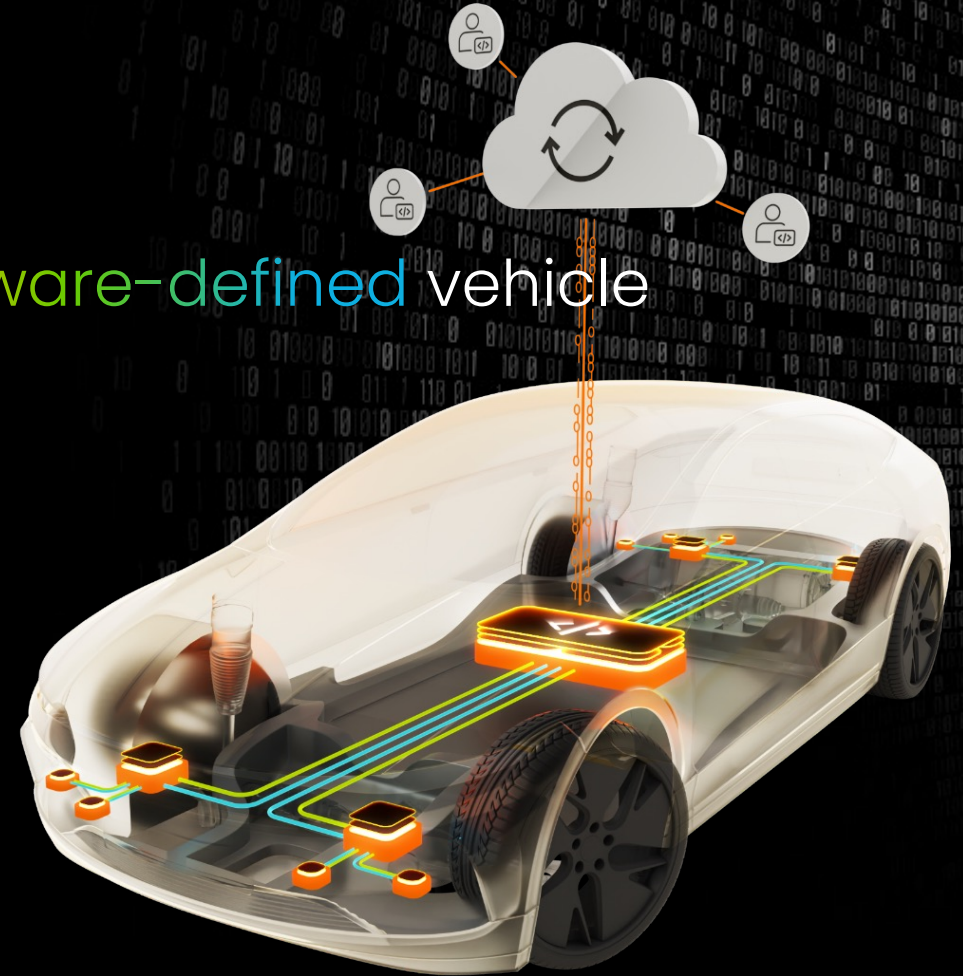
From hardware-oriented vehicle to software-defined vehicle



Static

Best performance when new

Loses value over time

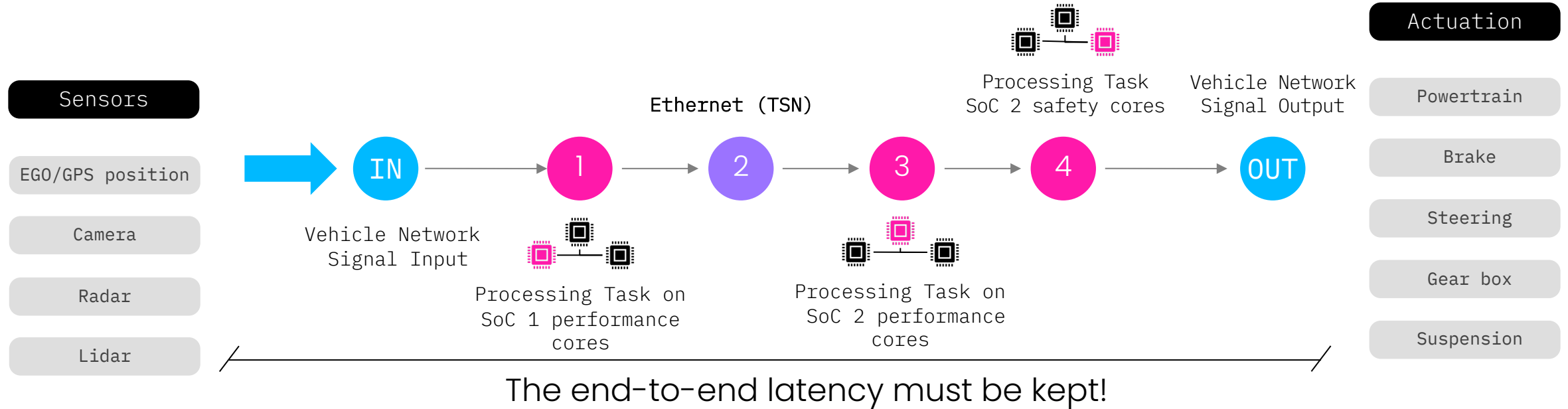


Dynamic, updatable

Performance increases over time

Value increases over time

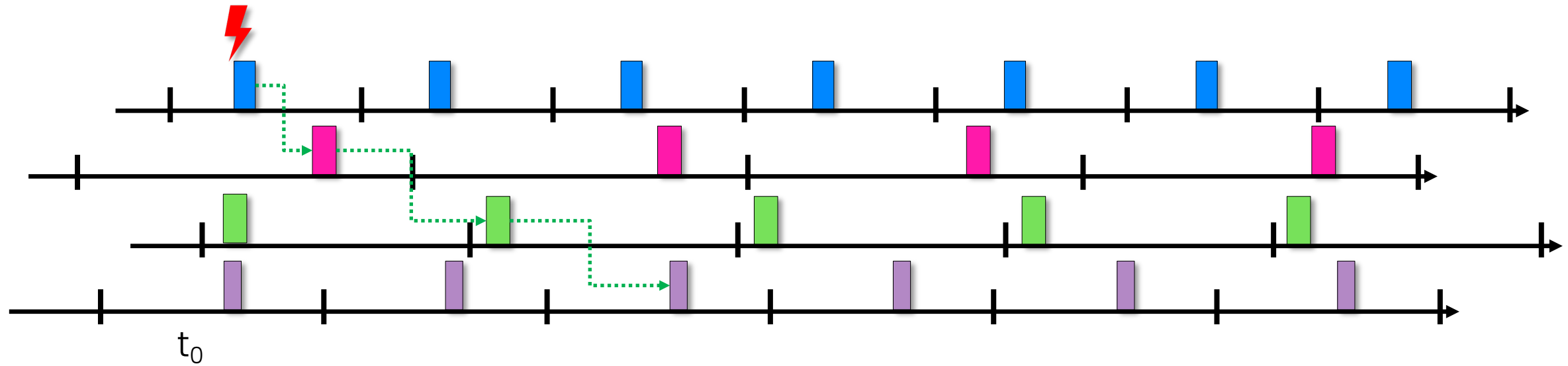
Cause-effect Chains



Cause-effect chains are common in automotive systems:

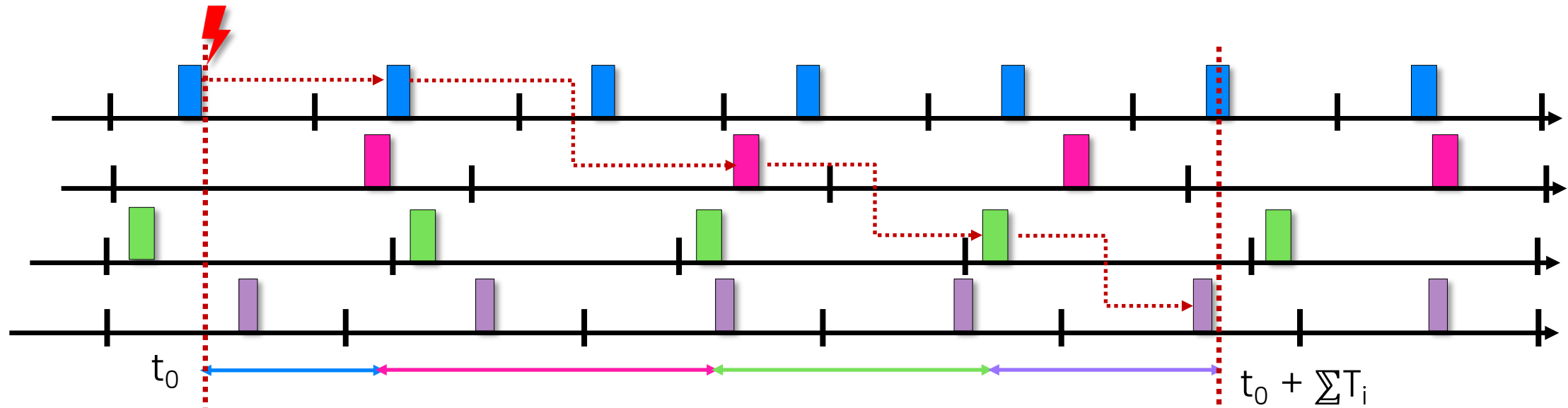
- timing and dependency requirements on the execution of tasks **and** transmission of messages
- can span across multiple activation patterns
- maximum end-to-end latencies and data age requirements
- go across SoCs and CPUs

Cause-effect Chains



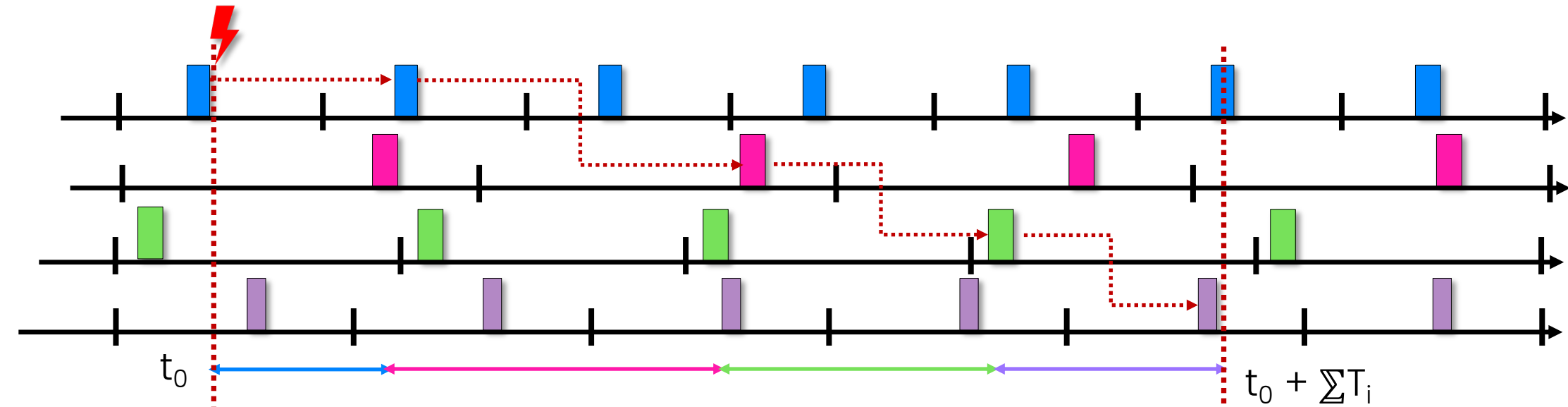
S. Craciunas, M. Becker, and P. Pop, "Automotive cause-effect chains in the wild: A real-world industrial benchmark and generator," 2026, presented at RTSOPS.

Cause-effect Chains



S. Craciunas, M. Becker, and P. Pop, "Automotive cause-effect chains in the wild: A real-world industrial benchmark and generator," 2026, presented at RTSOPS.

Cause-effect Chains



>> $b \geq \sum T_i$

Budget tightness

$\rho = b / \sum T_i$ median 0.72 · mean 1.00 · p_{10} 0.36 · p_{90} 1.43

ρ bin	n	share
[0.20, 0.40)	4	10.3 %
[0.40, 0.60)	4	10.3 %
[0.60, 0.80)	12	30.8 %
[0.80, 1.00)	3	7.7 %
[1.00, 1.50)	12	30.8 %
[2.00, 3.00)	4	10.3 %

S. Craciunas, M. Becker, and P. Pop, "Automotive cause-effect chains in the wild: A real-world industrial benchmark and generator," 2026, presented at RTSOPS.

Shaping profiles

The two profiles mandate near-disjoint mechanism sets



IEC/IEEE 60802 : 2026

TAS required at 100 Mbit/s and 1 Gbit/s

FP req



IEEE 802.1DG : 2025

ATS & CBS mandatory,
on the 2 highest traffic classes

***“Can there be a role for TAS or CQF in an Automotive Network?
NO, not in the converged core network carrying a mix of
streams with different latency and bandwidth requirements”¹***

¹https://some-ip.com/tsn-training-aec-2023/2023_AEC-TSN-Workshop-final_v1.pdf

Leaving TAS as optional institutionalizes ATS/CBS for automotive.

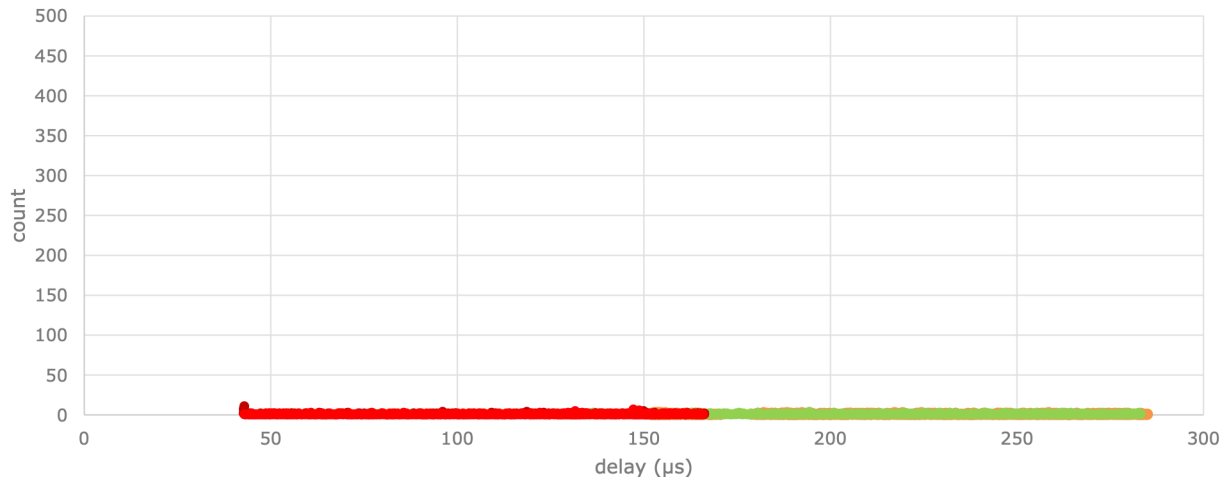
Is there a role for TAS in automotive networks?

"The worst-case effect of lower priority Flows on the latency of higher priority Flows is much larger for TAS than for Strict Priority Queuing (SP), Credit Based Shaper (CBS), or Asynchronous Traffic Shaper (ATS)"¹

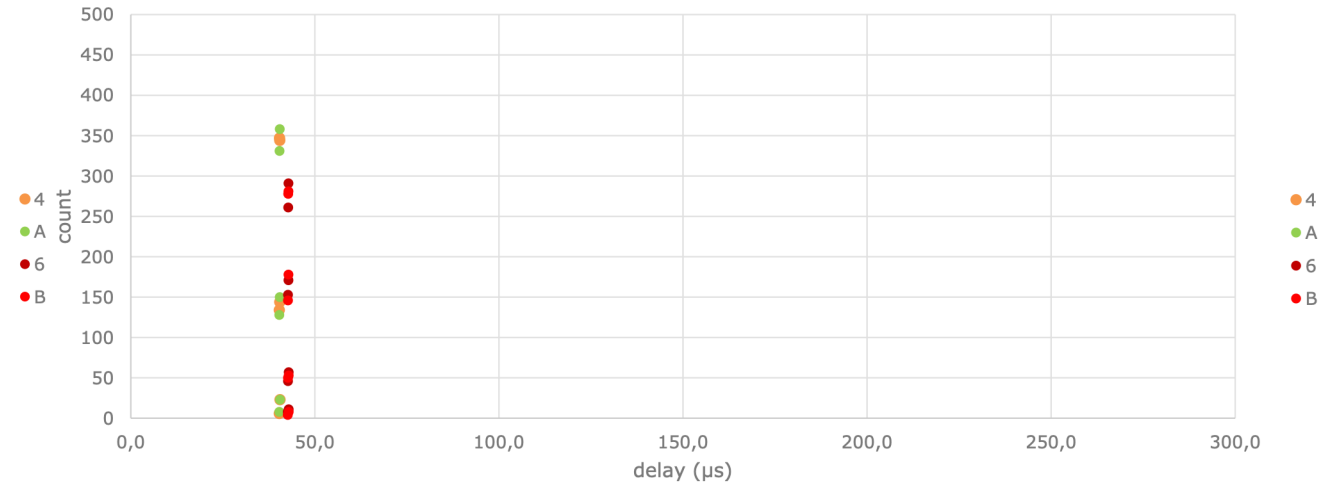


Measured worst-case latency on automotive HW. A single interferer separates the mechanisms by a factor of 6.²

802.1Qav with interfering traffic over 2 hops



802.1Qbv with interfering traffic over 2 hops

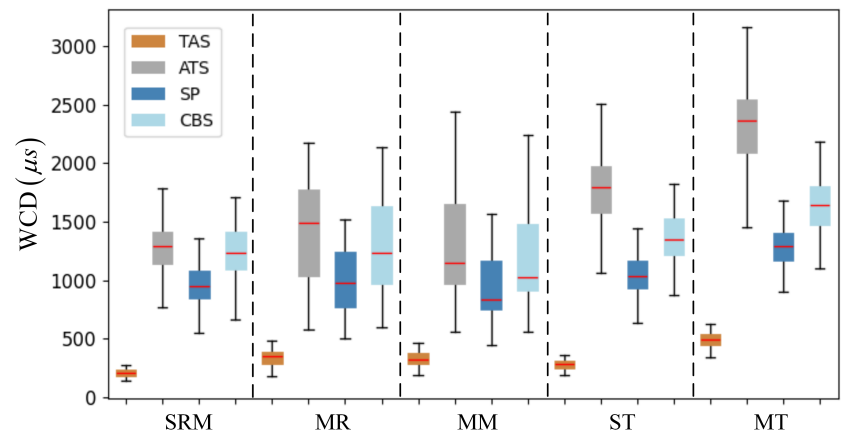


¹ https://some-ip.com/tsn-training-aec-2023/2023_AEC-TSN-Workshop-final_v1.pdf

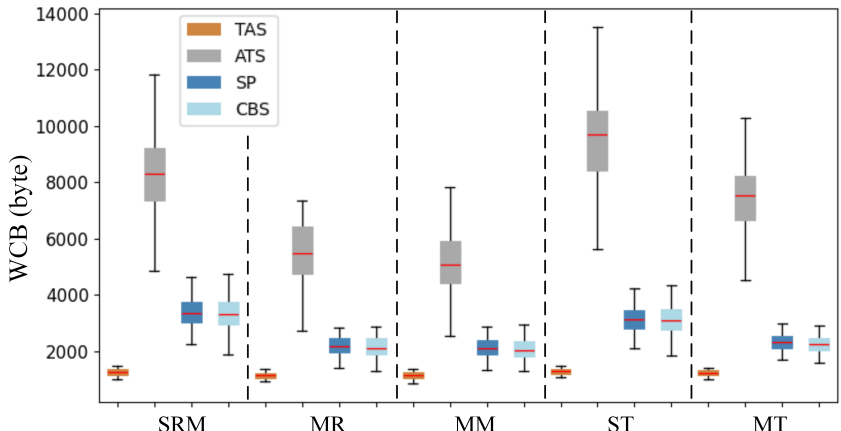
² https://www.ieee802.org/1/files/public/docs2021/dg-janker-delay-measuement-results-automotive_0621-v01-1.pdf

Comparing individual shapers

SRM small ring & mesh · MR medium ring · MM medium mesh · ST small tree, depth 1 · MT medium tree, depth 2



(a) End-to-end latency bounds



(b) Backlog bounds

TAS

TT scheduled by TAS has the highest performance, with ultra-low latency, jitter and backlog.

SP · CBS

SP is more beneficial for prio traffic; CBS can specify bandwidth reservations for each traffic class.

CBS vs SP

Backlog upper bounds of AVB traffic are lower with CBS than with SP.

ATS · HIGH PRIO

ATS has limited advantages for high-priority traffic when its load is under 80%.

ATS · LOW PRIO

ATS has more benefits for low-priority traffic when its average load is about 20%.

Complexity

"Dependencies on e.g., topology, mode of operation, line rates, and traffic characteristics make it difficult to compute Gate Control Lists for even simple network topologies and few Flows" ¹

TIME-GATED

Cost is up front

- GCL synthesis is NP-complete; exact formulations hit their limits on moderate networks
- Tailored heuristics still schedule 2000 nodes and >10K flows within an hour²
- An in-vehicle backbone is orders of magnitude smaller than that

ASYNCHRONOUS · ATS/CBS

Cost moves downstream

- Assigning streams to at most 8 traffic classes is itself a discrete optimization problem
- Coupled shaper parameters must still be derived
- Computing tight worst-case bounds can itself be NP-complete³

IEEE 802.1DG

Where no analysis is mandated, the complexity discussion is dropped.

IEC/IEEE 60802

Mandates TAS without talking about the synthesis complexity.

¹ https://some-ip.com/tsn-training-aec-2023/2023_AEC-TSN-Workshop-final_v1.pdf

² M. Vlk, K. Brejchova, Z. Hanzalek, S. Tang, "Large-scale periodic scheduling in time-sensitive networks," Computers & Operations Research, vol. 137, 2022.

³ A. Bouillard, L. Jouhet, and E. Thierry, "Tight performance bounds in the worst-case analysis of feed-forward networks," in INFOCOM, 2010.

Complexity

"Dependencies on e.g., topology, mode of operation, line rates, and traffic characteristics make it difficult to compute Gate Control Lists for even simple network topologies and few Flows"¹

TIME-GATED

Cost is up from

- GCL synthesis limits on model
- Tailored heuristics for flows within
- An in-vehicle smaller than

ASYNCHRONOUS · ATS/CBS

The choice between TAS and CBS/ATS does not change the complexity of the problem!

It rather affects the tools/methodology (=models/algorithms) available to tame this complexity!

IEEE 802.1DG

Where no analysis is mandated, the complexity discussion is dropped.

IEC/IEEE 60802

Mandates TAS without talking about the synthesis complexity.

¹ https://some-ip.com/tsn-training-aec-2023/2023_AEC-TSN-Workshop-final_v1.pdf

² M. Vlk, K. Brejchova, Z. Hanzalek, S. Tang, "Large-scale periodic scheduling in time-sensitive networks," Computers & Operations Research, vol. 137, 2022.

³ A. Bouillard, L. Jouhet, and E. Thierry, "Tight performance bounds in the worst-case analysis of feed-forward networks," in INFOCOM, 2010.

Combining shapers

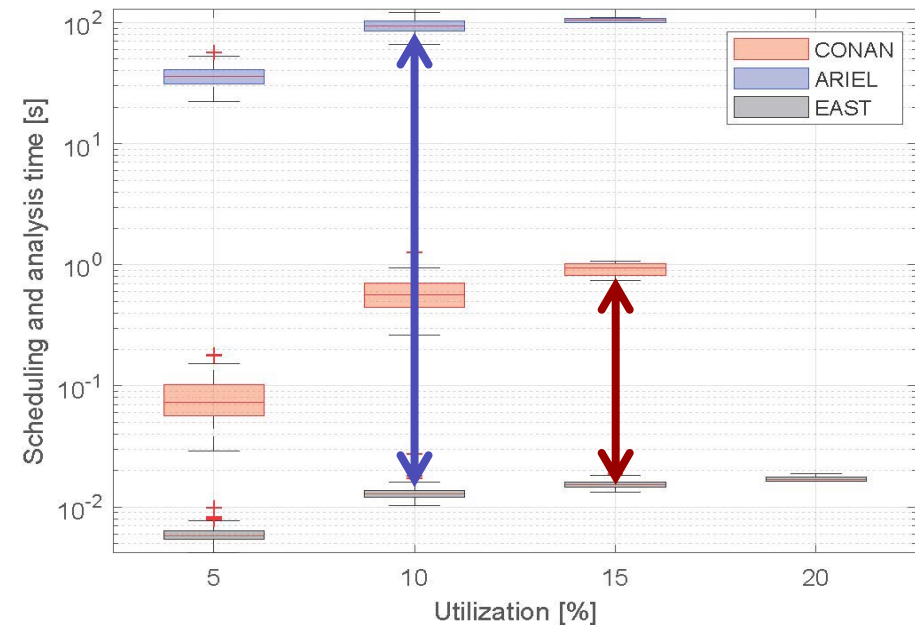


Profiles analyze mechanisms in isolation, but industry deploys them in combination.

“Due to the complexity of the configuration interdependency, we do not encourage to use TAS in combination with CBS or ATS on the same egress port!”¹

EAST efficient TAS and CBS integration²

- Decouples AVB analysis from ST scheduling using Max_STI constraints
- Achieves similar schedulability with orders-of-magnitude faster runtime than prior approaches
- Support for online and dynamic TSN reconfiguration
- Opens the door to a joint optimization of routing, AVB configuration, and scheduling



¹ https://some-ip.com/tsn-training-aec-2023/2023_AEC-TSN-Workshop-final_v1.pdf

² D. Bujosa, S.S. Craciunas, and S. Mubeen - Efficient AVB-aware Scheduling for Critical Traffic in Time-sensitive Networks. In Proc. RTAS, IEEE, 2026.

Conclusions – an opportunity (and call) for academia to step in

Profiles do not impose a mechanism, and arguably should not. **That leaves a role open!**

- Profiles settled what vendors must build and, quite reasonably, left the rest to the integrator.
- Nothing downstream picked it up, and the decisions they left open are where academia can step up.
- Tooling can be left for vendors to compete.

Where academia can help

01

Which mechanisms and combinations serve which traffic & application classes?

Do this as evidence, not as a requirement!

02

Which mechanisms are genuine substitutes, which combinations do not compose, which do not belong in a given use case

03

Quantify what is bought and what is paid when complexity shifts from synthesis to verification

04

Methods for compositional analysis, capability-aware synthesis

05

A portable way to state requirements and check them independently. Verification is a major pain point!

06

Publish negative results!

Thank you!



silviu.craciunas@nxp.com



<https://scraciunas.github.io/>



www.linkedin.com/in/scraciunas



EMSOFT Special Session:
Making Time-Sensitive Networking Deployable:
A Comprehensive Lifecycle Architecture

www.trustmotion.com



 trustmotion
part of NXP