# Frame latency evaluation: when simulation and analysis alone are not enough

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# Outlook

1. **Context:** early design phases where only simulation and analysis are available
2. **Goal:** see how simulation and analysis compare and point out their pitfalls
3. **Method:** insight from experiments on Controller Area Network

# Why timing verification is required





- **Verify that performance requirements are met: deadlines, jitters, throughput**
- **Select the hardware / software components: optimize costs**
- **Meet some certification level: e.g., avionics, railway systems, power plants, etc**

Timing models: trade-off to be found between accuracy / complexity / computing time



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# RTaW mission: help designers build truly safe and optimized systems

- **Activities:** Model-Based Design, dependability, formal and temporal verification
- **Communications systems :** CAN, AFDX, FlexRay, SpaceWire, industrial Ethernet, TTP, etc …
- **Verification techniques:** **schedulability analysis**, network-calculus, model-checking and **simulation**
- **Domains:** aerospace, automotive and industry at large

In our experience, 2 cases for timing verification :

✓Certification is mandatory (e.g., DO178B - DAL A): well accepted

✓No certification : various practices / levels of acceptance



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# Type A: no timing validation whatsoever (early in the V-cycle)

**Practice: Carry-over of existing (proven in use) systems with domain-specific rules:**

"The load on an automotive CAN network must not be higher than 30%"

"A frame pending for transmission for more than 30ms is cancelled out"

etc…

✓Sub-optimal design : e.g., does one really need 5 (or more) distinct CAN buses in a car?!

✓Potentially unsafe design with problems that are hard to reproduce and are costly to repair later …

# Type B: simulation is enough, worst-case never occurs anyway!

**Practice: software simulations, then simulations with HiL (Hardware in the Loop) as the ECUs become available …**

✓Hardware resources (too?) well optimized

✓Unsafe results because the worst-case sometimes occurs (and may even last for a long time, see preliminary results later in the presentation)

A question that remain mainly open in timing verification :
"How often does the worst-case actually occur ? "
First, get some insight with experimentations …



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# Type C: analysis says the system is safe, so we are covered …

**Practice: use some black-box software that implements worst-case timing analysis and concludes about the feasibility of the system**

- ✓Sub-optimal design sometimes because overestimations / pessimistic assumptions add up
- ✓Potentially unsafe design :
  - software are error-prone,
  - not everything is accurately modeled
  - analytic models – especially unpublished complex ones – can be wrong



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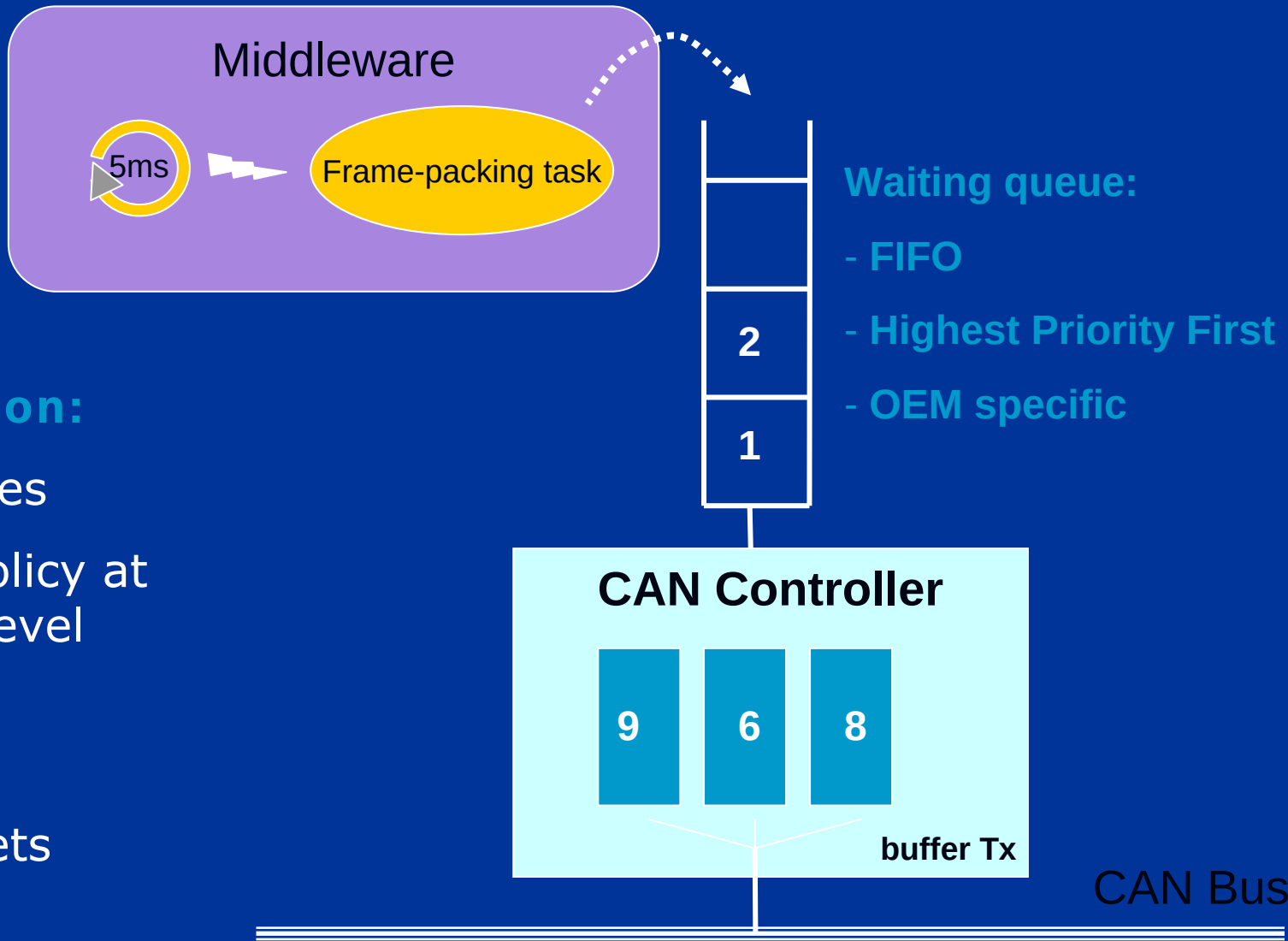
# Experimental setup

# CAN communication stack a simplified view




**Requirements on temporal verification:**

- ✓ handle 150+ frames
- ✓≠ waiting queue policy at the microcontroller level
- ✓ limited number of transmission buffers
- ✓ handle frame offsets



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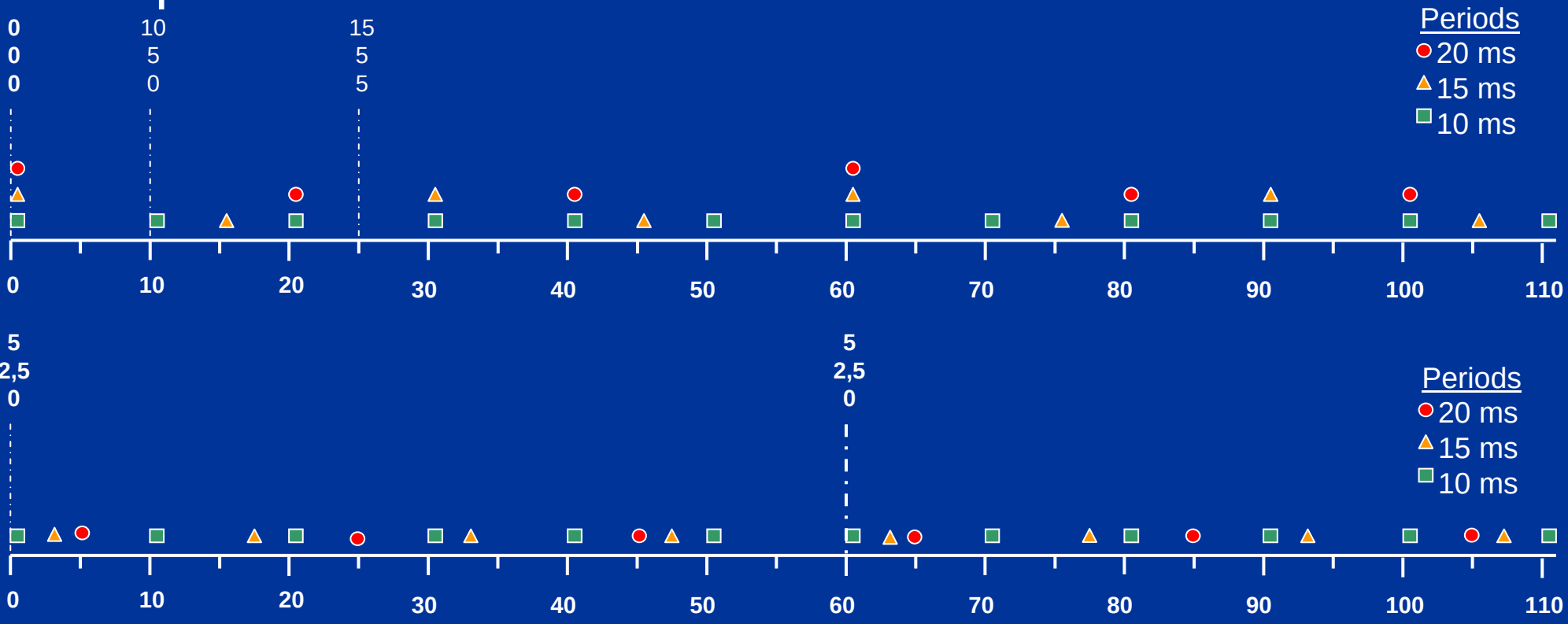
# Scheduling frames with offsets ?!

**Principle:** desynchronize transmissions to avoid load peaks

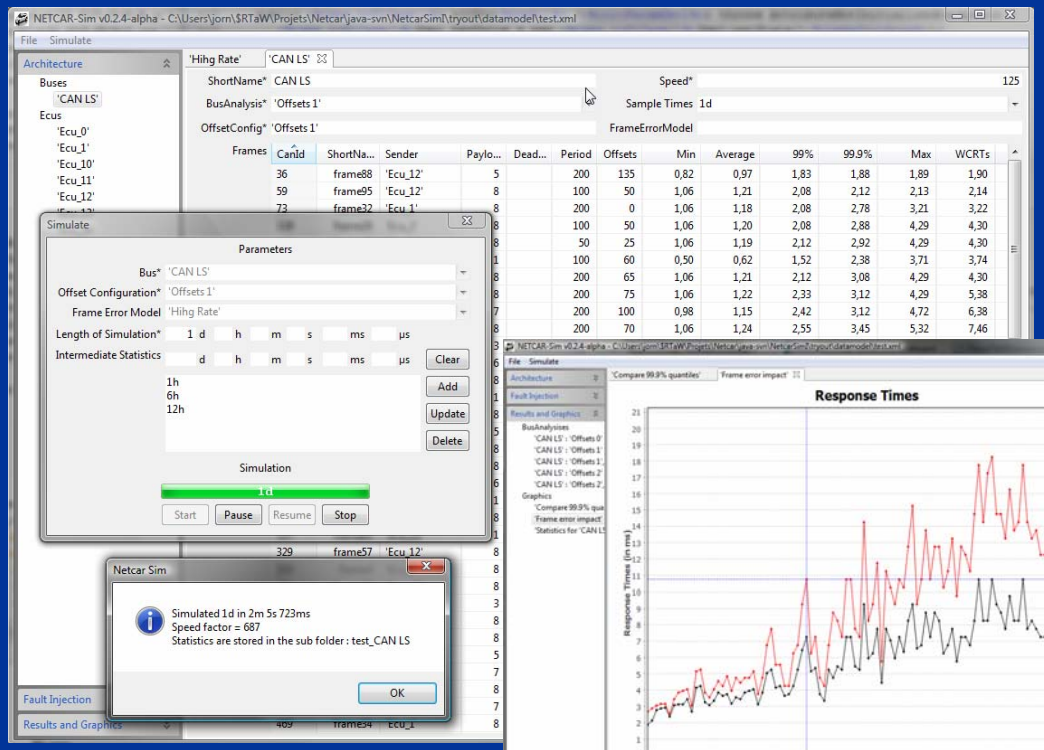


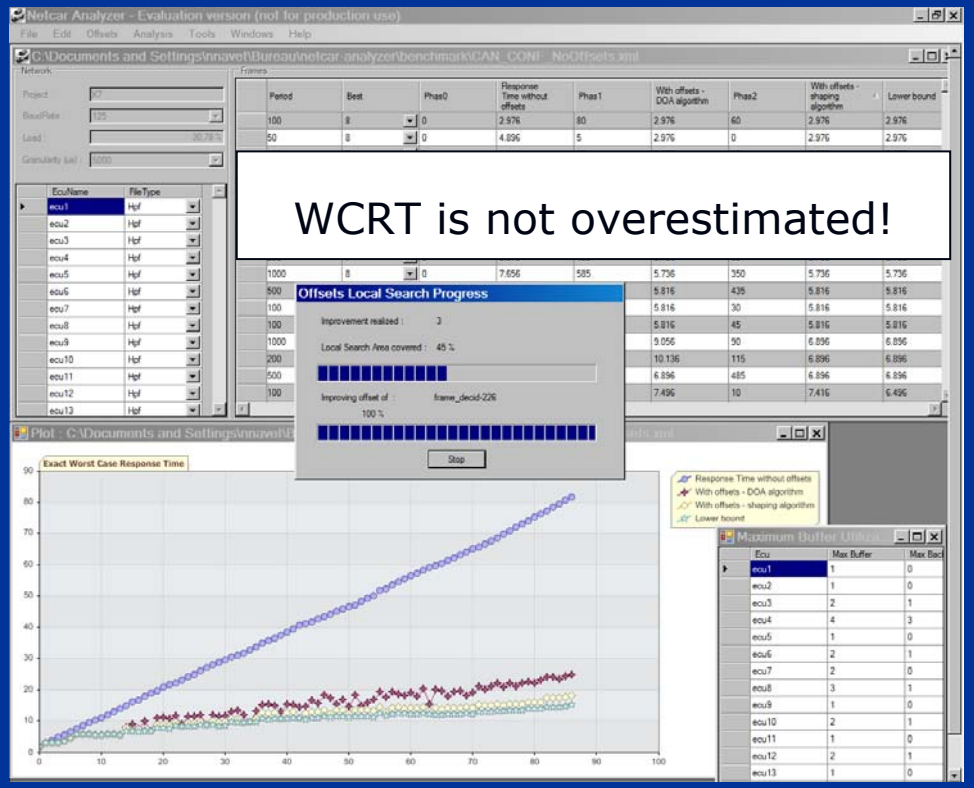

**Algorithms** to decide offsets are based on arithmetical properties of the periods and size of the frame

# Network configuration

| | |
|---|---|
| **Network** | Controller Area Network 125 kbit/s |
| **Set of messages** | Automotive body network generated with NETCARBENCH [8]<br>http://www.netcarbench.org |
| **# ECUs** | 15 |
| **# frames** | 145 |
| **Workload** | 50.5% |
| **Periods** | [50,2000ms] with distributions from an existing car |
| **Frame offsets** | Optimized with DOA algorithm [3] |
| **Inter-ECU offsets** | All offsets are possible (clock drifts, ECU reboots, ECU boot sequence depends on sleep mode, etc) |
| **ECU clock drifts** | 3 cases: no drift, ±1ppm, ±1000ppm |

# RTaW software used in the study




WCRT is not overestimated!

**RTaW-Sim :** Fine-Grained **Simulation** of Controller Area Network with Fault-Injection Capabilities

**NETCAR-Analyzer :** Timing **Analysis** and Resource Usage Optimization for Controller Area Network (© Inria/Inpl)

RTaW-Sim freely available at http://www.realtimeatwork.com starting from June 2010



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# On why we should not trust **analytic models** for worst-case frame latency evaluation



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# Types of results achievable with worst-case analysis

## Max buffer utilization

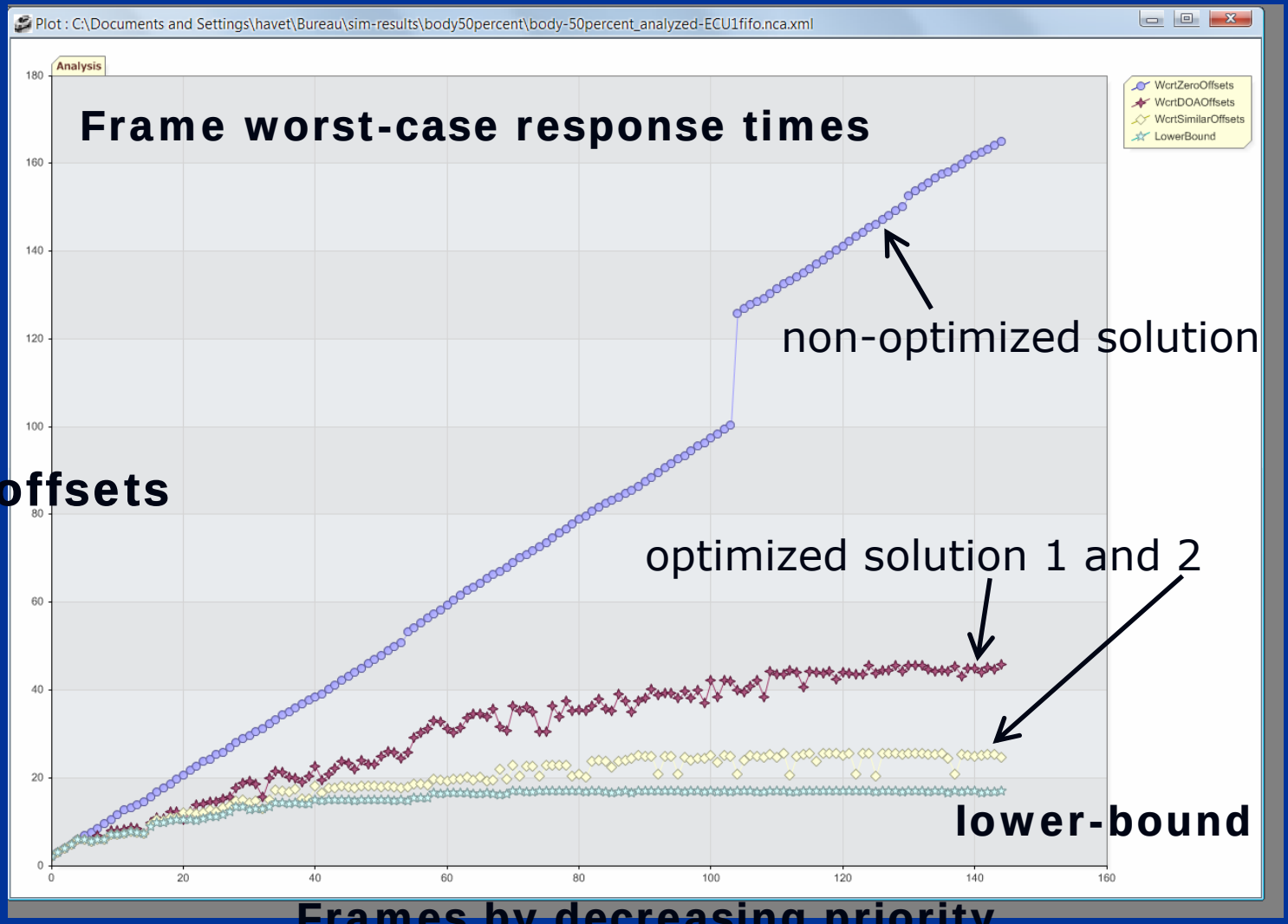
Maximum Buffer Utilization Pha...

| | Ecu | Max Buffer | Max BackLog |
|---|---|---|---|
| ▸ | Ecu_0 | 2 | 0 |
| | Ecu_1 | 8 | 6 |
| | Ecu_2 | 6 | 5 |
| | Ecu_3 | 4 | 3 |
| | Ecu_4 | 2 | 1 |
| | Ecu_5 | 2 | 1 |
| | Ecu_6 | 2 | 1 |
| | Ecu_7 | 2 | 1 |
| | Ecu_8 | 3 | 2 |
| | Ecu_9 | 2 | 1 |
| | Ecu_10 | 2 | 1 |
| | Ecu_11 | 2 | 1 |
| | Ecu_12 | 1 | 0 |
| | Ecu_13 | 3 | 2 |
| | Ecu_14 | 1 | 0 |
| * | | | |

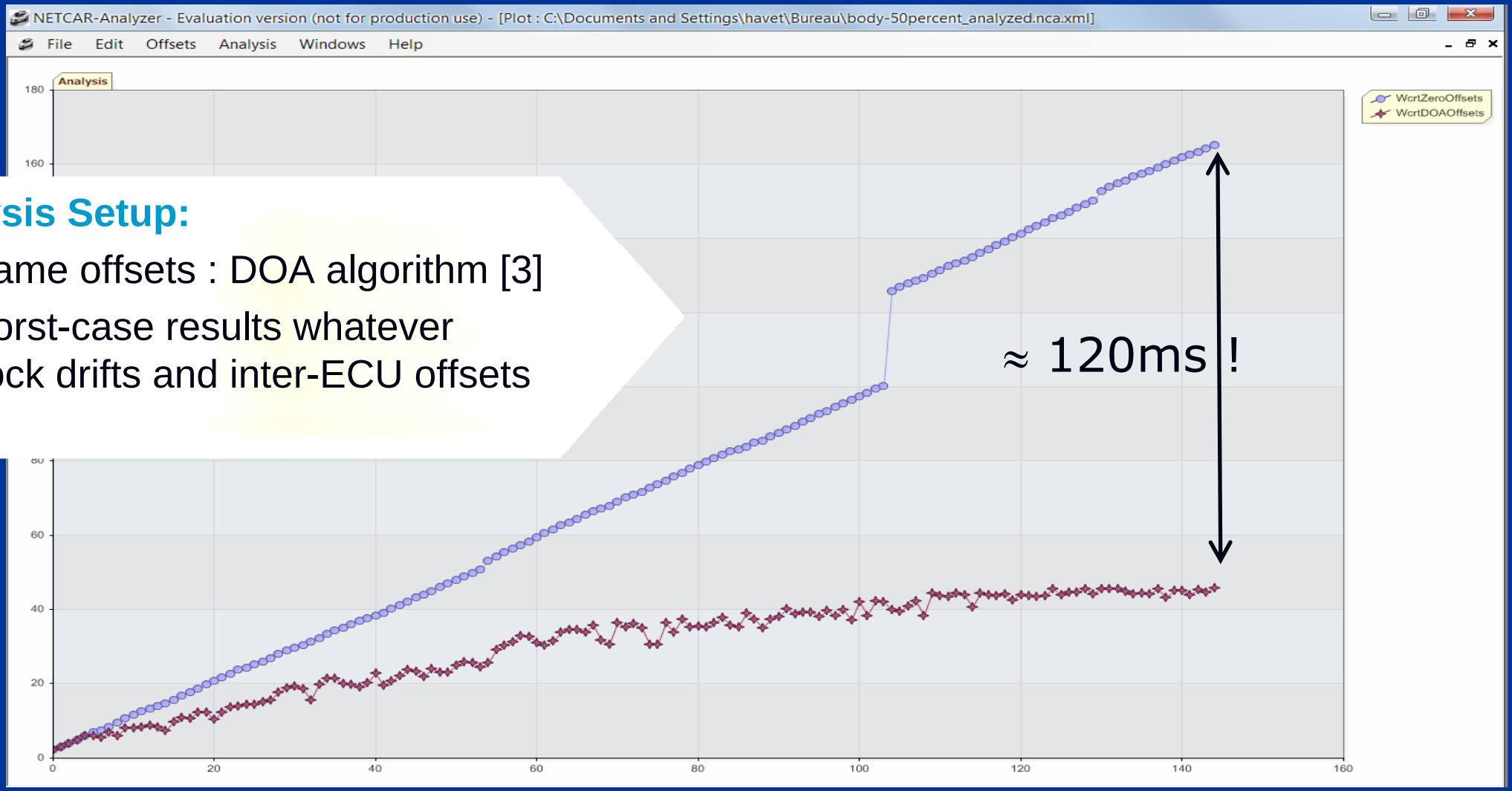
## Worst-case inter-ECU offsets

WCRT Scenario frame61

| | Ecu | Phase |
|---|---|---|
| ▸ | Ecu_0 | 750 |
| | Ecu_1 | 1735 |
| | Ecu_2 | 665 |
| | Ecu_3 | 1485 |
| | Ecu_4 | 1810 |
| | Ecu_5 | 1300 |
| | Ecu_6 | 1805 |
| | Ecu_7 | 665 |
| | Ecu_8 | 520 |
| | Ecu_9 | 160 |
| | Ecu_10 | 610 |
| | Ecu_11 | 215 |
| | Ecu_12 | 65 |
| | Ecu_13 | 985 |
| | Ecu_14 | 0 |
| * | | |



# Analytic models need to be fine-grained frame offsets overlooked here …




**Analysis Setup:**

- Frame offsets : DOA algorithm [3]
- Worst-case results whatever clock drifts and inter-ECU offsets

To the best of our knowledge, there are no (usable) published results on this



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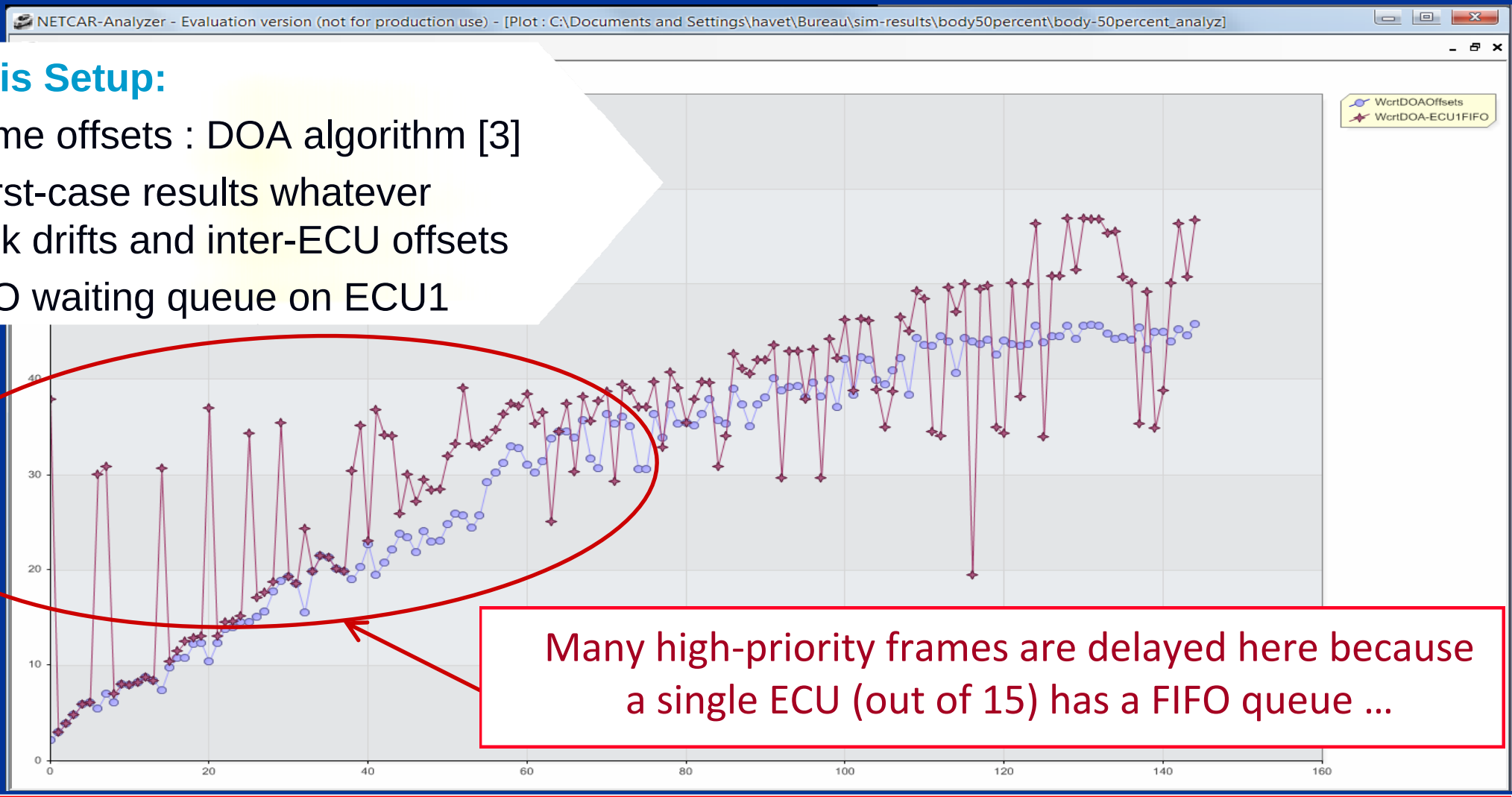
# Analytic model needs to be fine grained

## Frame waiting queue is FIFO on ECU1
## the OEM does not know or software cannot handle it …

**Analysis Setup:**

- Frame offsets : DOA algorithm [3]
- Worst-case results whatever clock drifts and inter-ECU offsets
- FIFO waiting queue on ECU1




Many high-priority frames are delayed here because a single ECU (out of 15) has a FIFO queue …



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# There is a gap between WCRT analytic models and reality IMHO

- Traffic is not always well caracterized and/or well modeled
  e.g. aperiodic traffic ?! see [5] for some solution
- Implementation choices really matter
  and standards do not say everything, eg. Autosar drivers
- Analytic models are often much simplified abstraction of reality
  - optimistic (=unsafe): FIFO queue, hardware limitations such as non-abortable transmissions [4,7], etc
  - overly pessimistic: e.g. overlooking frame offsets, aperiodic traffic modeled as sporadic, etc
- Analytic models are prone to errors
  remember " CAN analysis refuted, revisited, etc" [6] ?!

**Bottom line: do not blindly trust analytic models!**

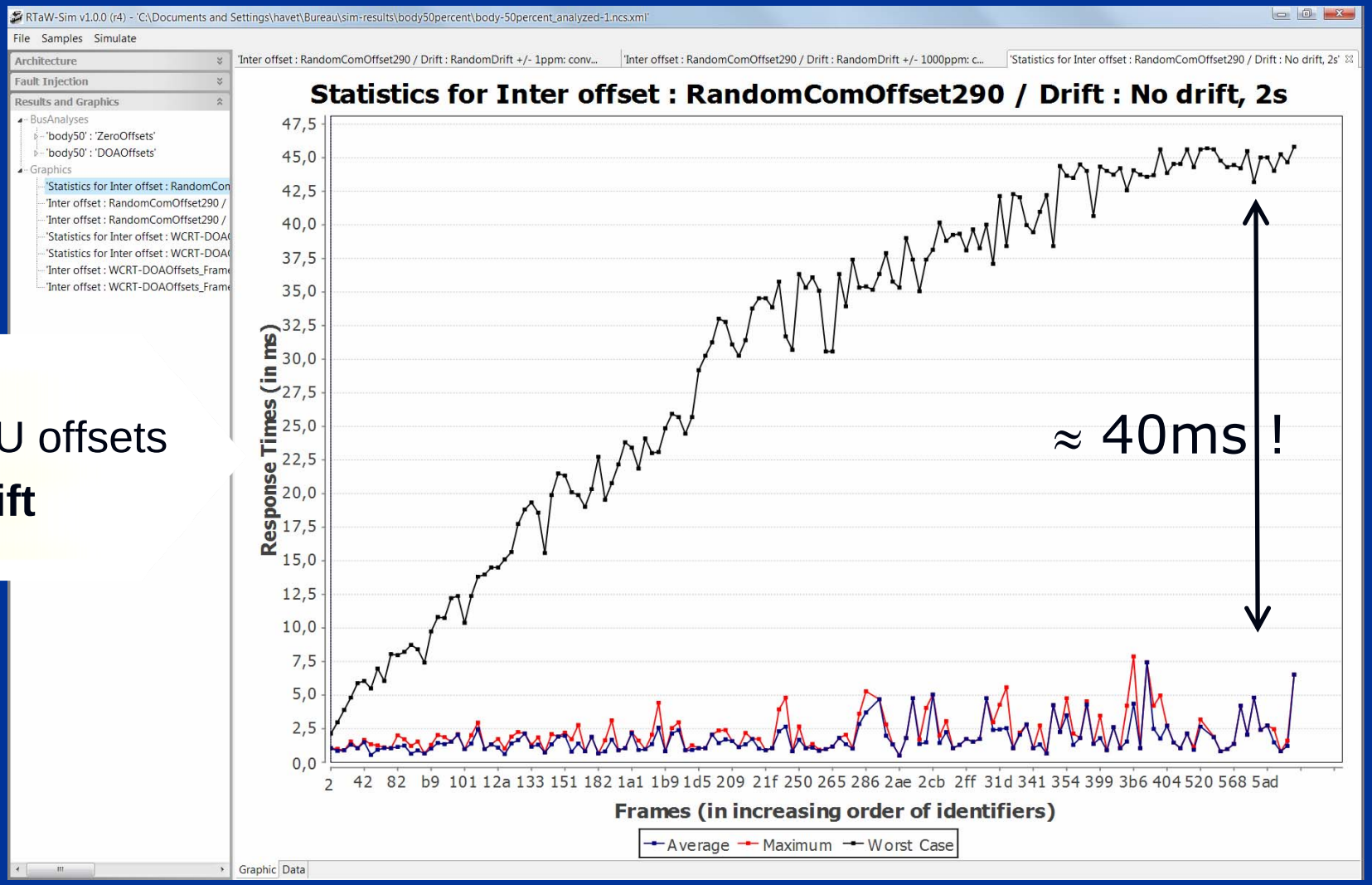
Systems should be conceived so as to be analyzable in temporal domain

# On why we should not trust **simulation models** for worst-case frame latency evaluation

# Are simulation results (max) close to worst-case response times ? Well …

**Simulation Setup:**

- Random inter-ECU offsets
- **no ECU clock drift**



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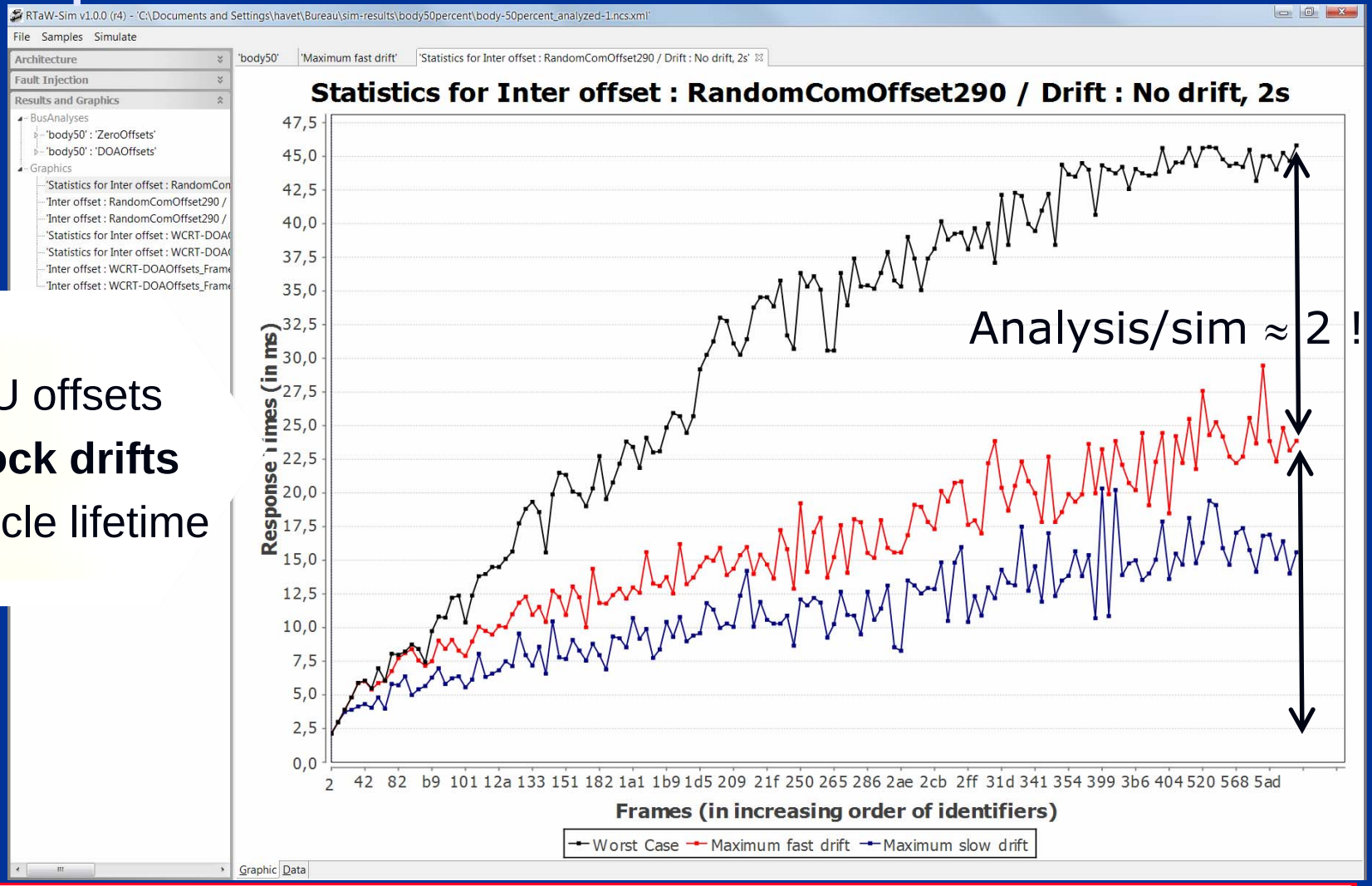
# Are simulation results (max) close to worst-case response times ? with clock drifts

**Simulation Setup:**

- Random inter-ECU offsets
- **Slow and fast clock drifts**
- Sim duration: vehicle lifetime

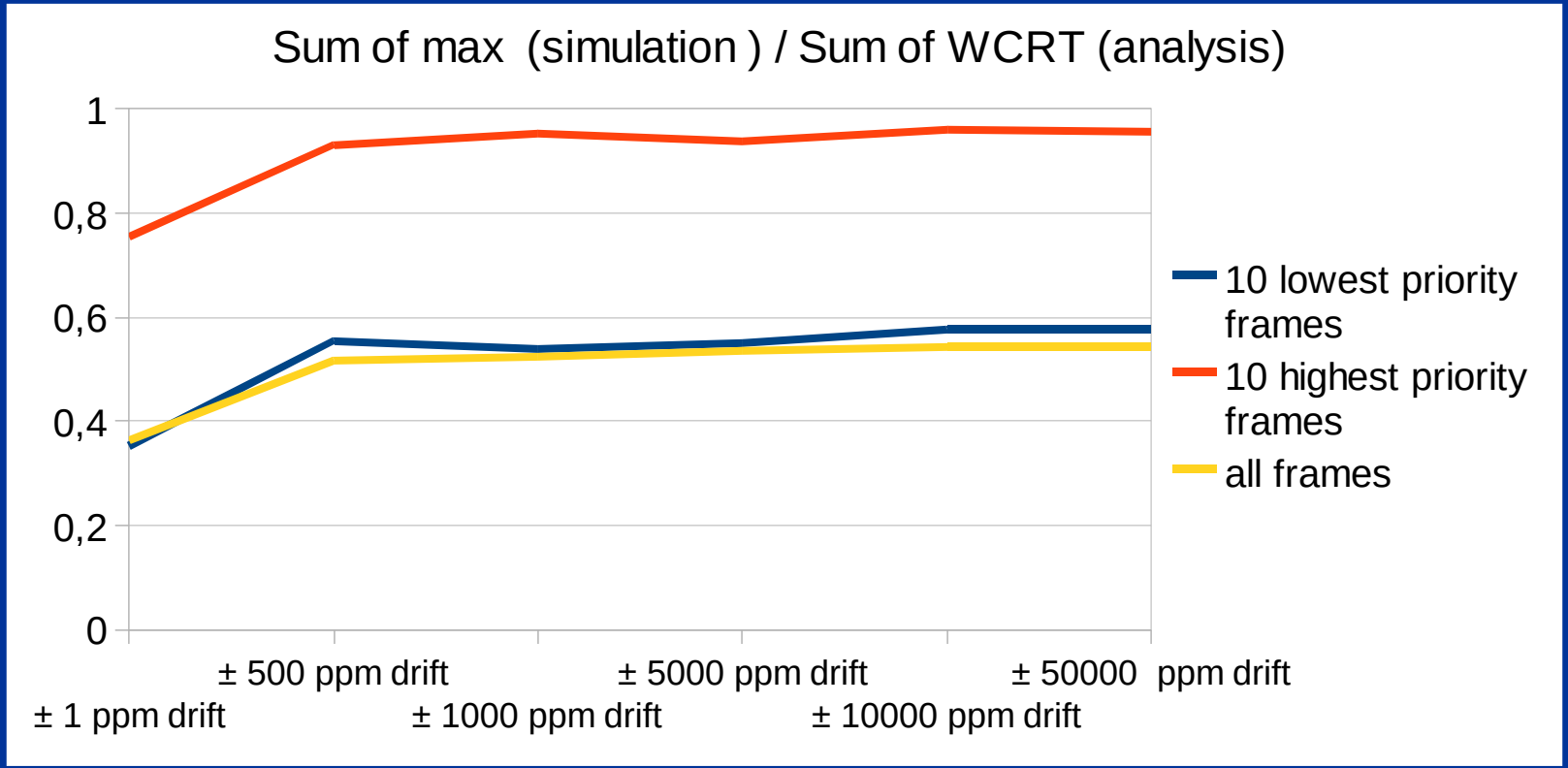



Whatever you do, you have little chance with simulation to find the worst-case!

# Are simulation results (max) close to worst-case response times ? with clock drifts

**Simulation Setup:**

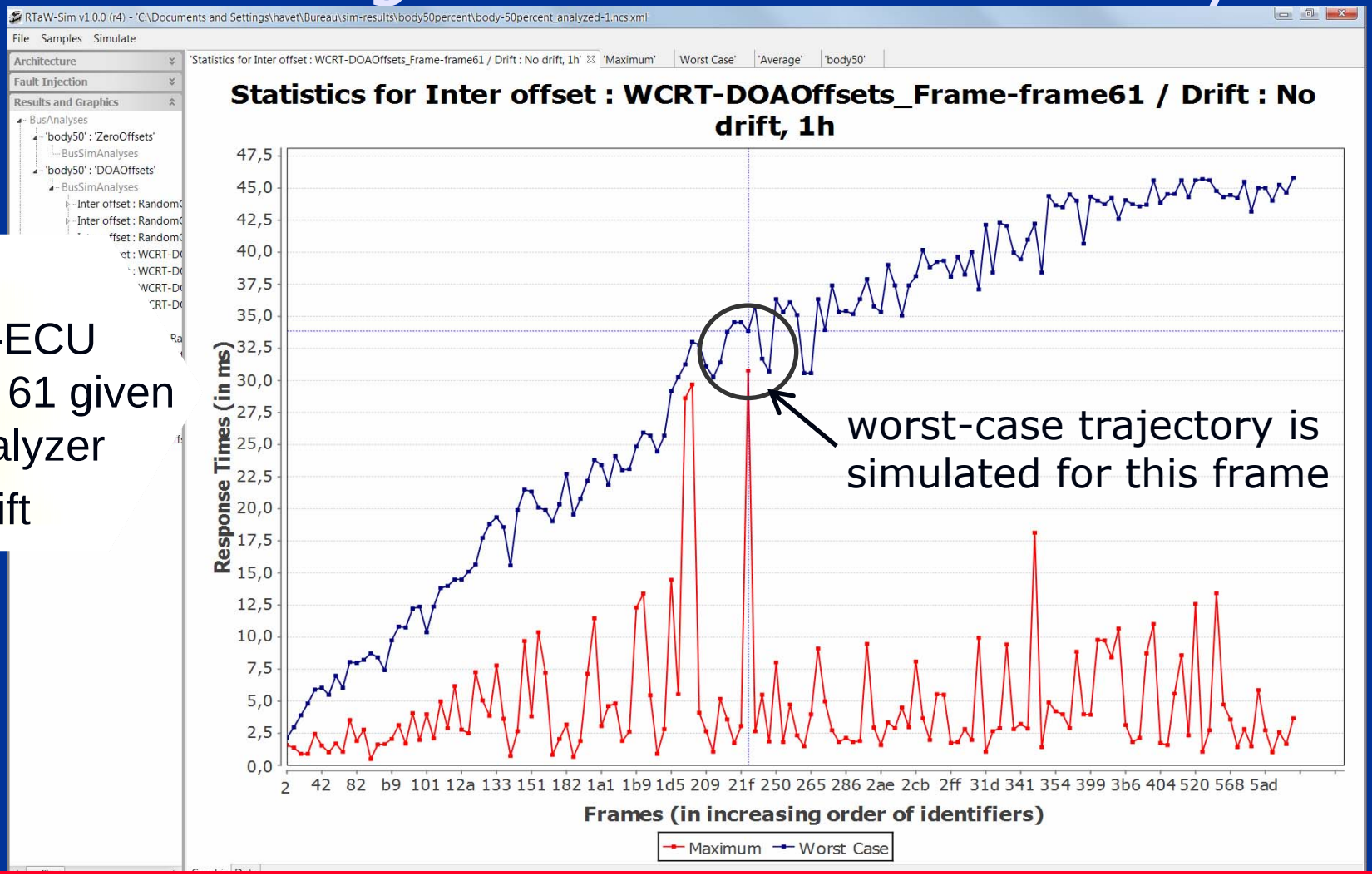
- Same as previous slide




Increasing the clock drift rate is not enough …

Knowing the analysis results – including here worst-case inter-ECU offsets for each frame - simulation becomes more useful

# Simulation helps validate assumptions made, correctness and tightness of WCRT analysis




**Simulation Setup:**

- worst-case inter-ECU offsets for frame 61 given by NETCAR-Analyzer
- no ECU clock drift

Difference comes here from the blocking factor that is not explicitly simulated



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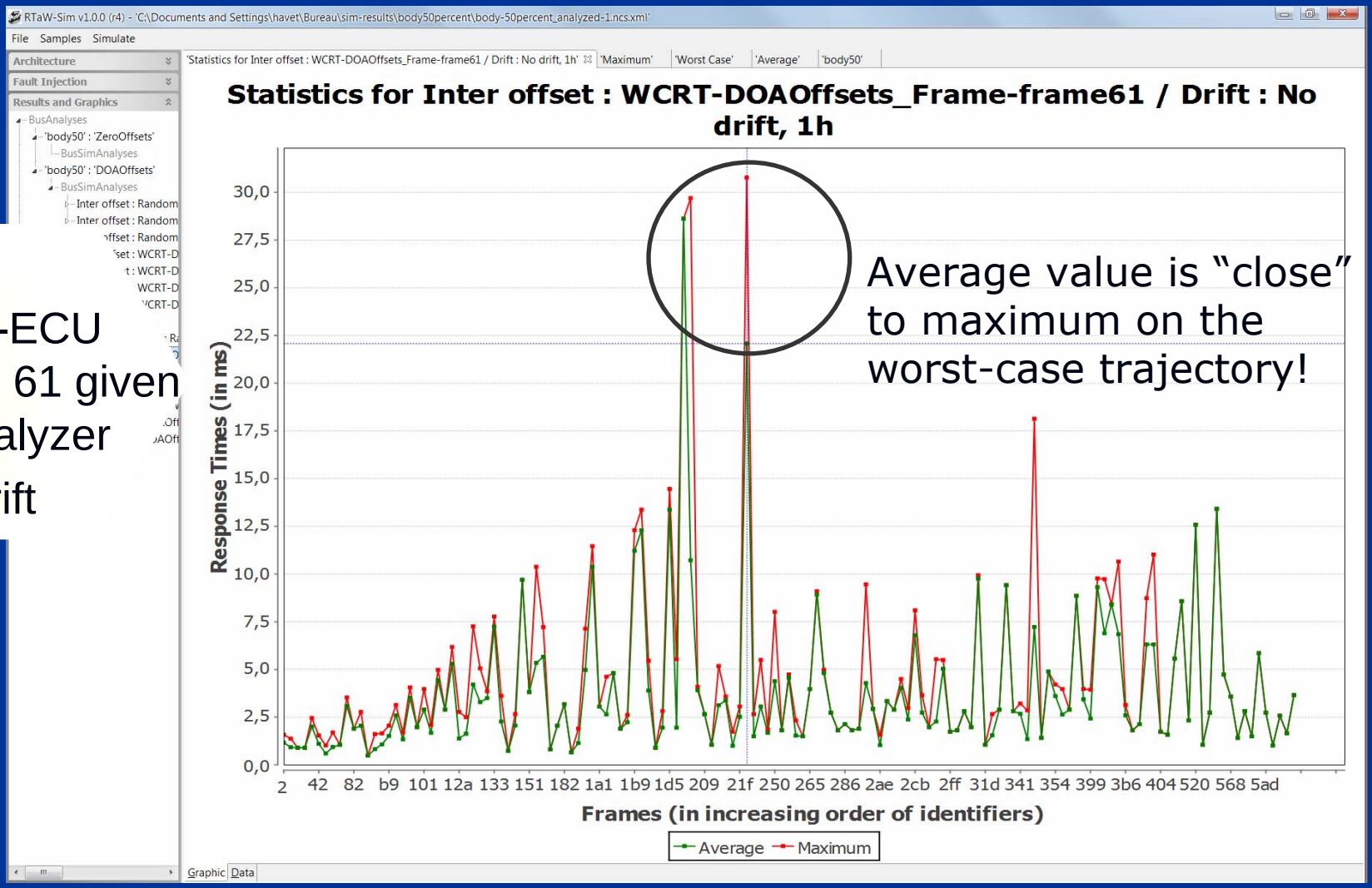
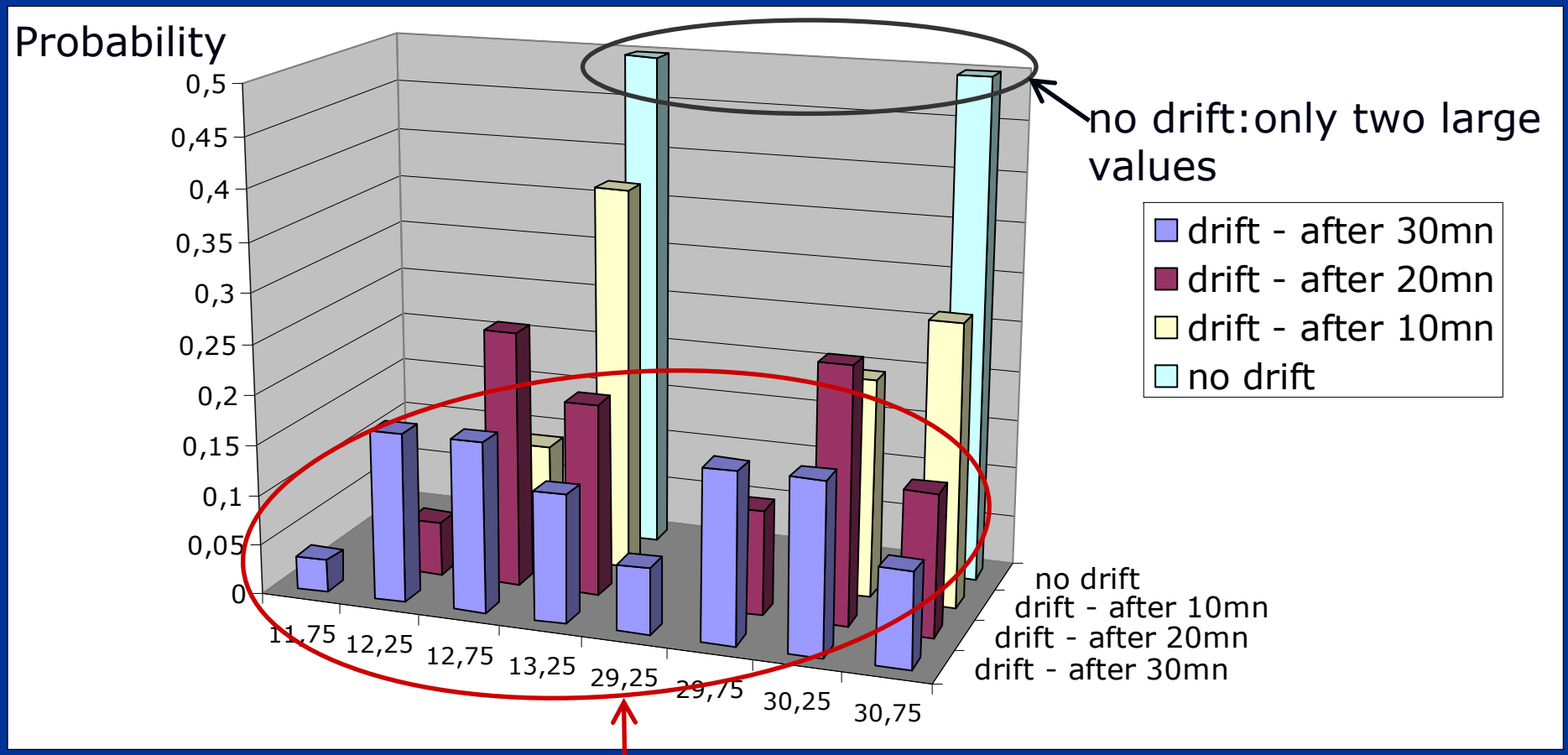
# How often does the worst-case occurs: very often on certain trajectories …

**Simulation Setup:**

- worst-case inter-ECU offsets for frame 61 given by NETCAR-Analyzer
- no ECU clock drift



# Distribution of response times for frame 61 with and without clock drifts




Even with clock drift, unusually large response times occur during more than 30mn!

# Conclusion: in the context of dependability constrained systems …

- Simulation is not enough and analytic models are usually much simplified, often pessimistic and sometimes even wrong
- Simulating the worst-case trajectory (and neighbours):
  - helps to validate analytic models : latencies, buffer occupation, etc
  - tells us about how long we stay in the worst-case situation
- Our ongoing work: how often does the worst-case actually occur? do we really need to dimension for the worst-case for a given a SIL level?
- Application to CAN, AFDX and switched Ethernet in aerospace, power plant and automotive domains



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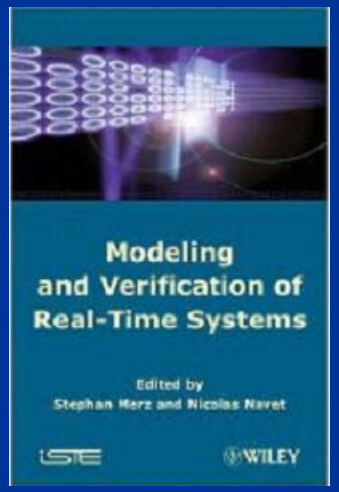
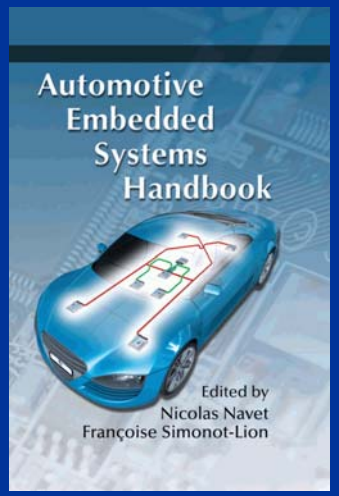
# References

# References

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[2] RealTime-at-Work (RTaW), A Fine-Grained Simulation of Controller Area Network with Fault-Injection Capabilities, freely available on RTaW web site: http://www.realtimeatwork.com, 2010.

[3] M. Grenier, J. Goossens, N. Navet, "Near-Optimal Fixed Priority Preemptive Scheduling of Offset Free Systems", Proc. of the 14th International Conference on Network and Systems (RTNS'2006), Poitiers, France, May 30-31, 2006.

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# Questions / feedback ?

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