BOOKOUT V. TOYOTA

2005 Camry L4
Software Analysis

Michael Barr

BARR group

The Embedded Systems Experts

MICHAEL BARR
Embedded Software Expert

Electrical Engineer (BSEE/MSEE)

Experienced Embedded Software Developer

- Named inventor on 3 patents

Consultant & Trainer (1999-present)

- Embedded Software Process and Architecture for reliability
- Various industries (e.g., pacemakers, industrial controls)

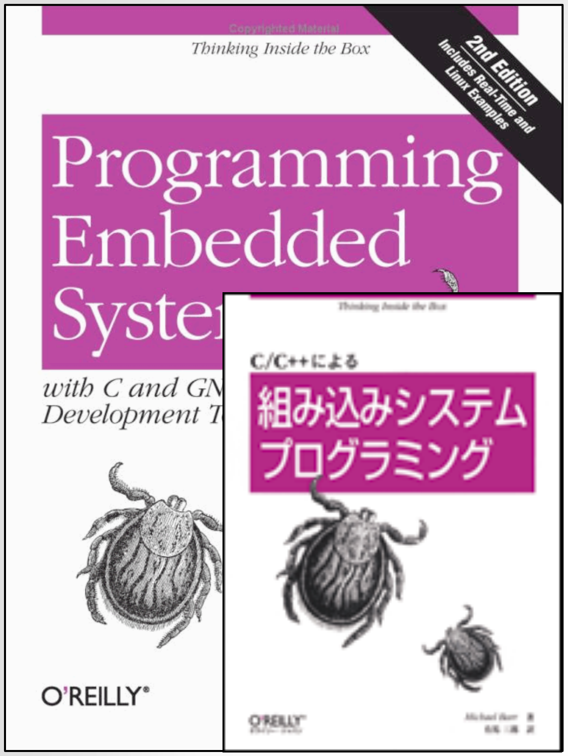
Former *Adjunct Professor*

- University of Maryland 2000-2003 (Design and Use of Operating Systems)
- Johns Hopkins University 2012 (Embedded Software Architecture)

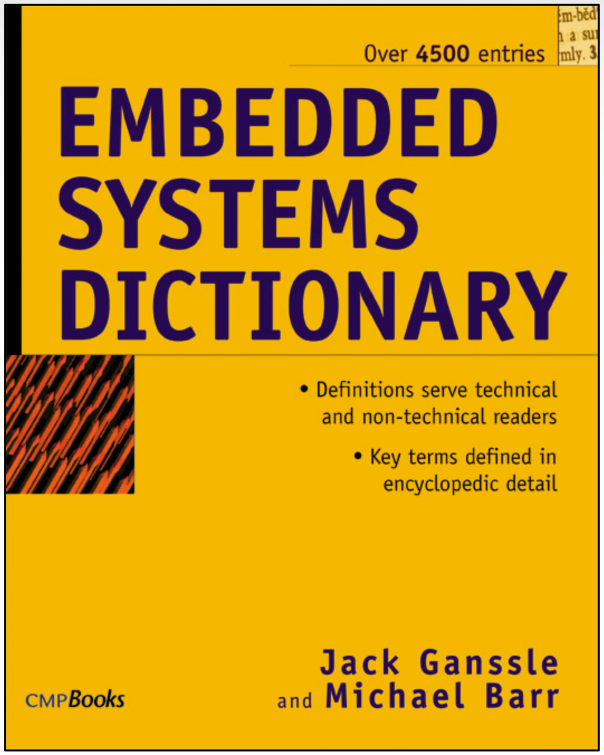
Served as *Editor-in-Chief*, *Columnist*, *Conference Chair*

Author of 3 books and 65+ articles/papers

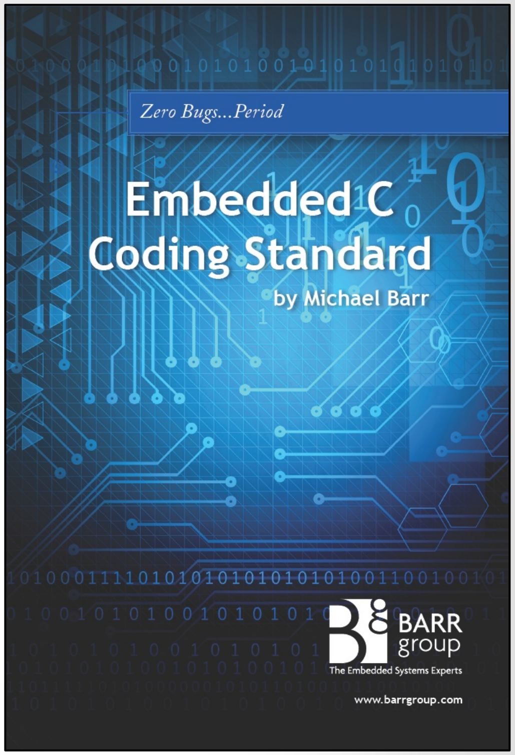
BOOKS BY MICHAEL BARR


Thinking Inside the Box
2nd Edition
Includes Real-Time and Linux Examples
Programming Embedded Syster
with C and GN
Development T
O'REILLY
C/C++による
組み込みシステムプログラミング
O'REILLY

1ed: 1999; 2ed: 2006


Over 4500 entries
EMBEDDED SYSTEMS DICTIONARY
• Definitions serve technical and non-technical readers
• Key terms defined in encyclopedic detail
Jack Ganssle and Michael Barr
CMPBooks

1ed: 2003



1ed: 2008; 2ed: 2012

EMBEDDED SYSTEMS DEFINED

"Embedded Systems"

- Electronics + software for a dedicated purpose
- Many billion more new embedded systems each year
  - microwave ovens, digital watches, pacemakers, thermostats
  - You are surrounded by them (like it or not; safe or not)

Embedded systems in cars

- Modern cars contain networks of embedded computers!
  - Anti-lock brakes, airbags, speedometer, GPS, radio, …
- Some carmakers brag over 100 microprocessors inside!
  - Each headlight, each mirror, each seat, …

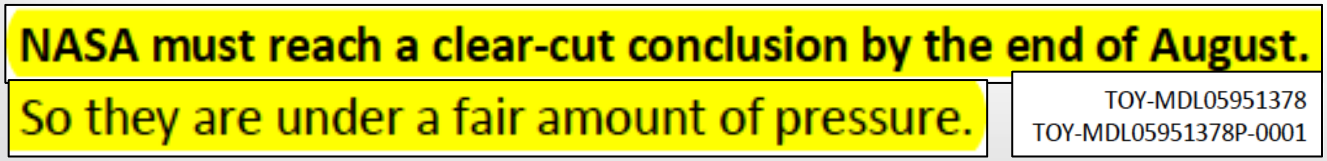
MY REVIEW OF TOYOTA’S SOURCE CODE

Access to Toyota’s “electronic throttle” source code

- In a secure room in Maryland
- Subject to confidentiality agreements
- For vehicle models with ETCS spanning ~2002-2010 model years
  - Camry, Lexus ES, Tacoma, and others

Approximately 18 months of calendar time with code

- By a very experienced team of embedded systems experts
  - Including 3 other engineers from Barr Group
- Building upon NASA’s earlier source code review; digging deeper



NASA must reach a clear-cut conclusion by the end of August.

So they are under a fair amount of pressure.

TOY-MDL05951378
TOY-MDL05951378P-0001

EXAMPLE C LANGUAGE SOURCE CODE

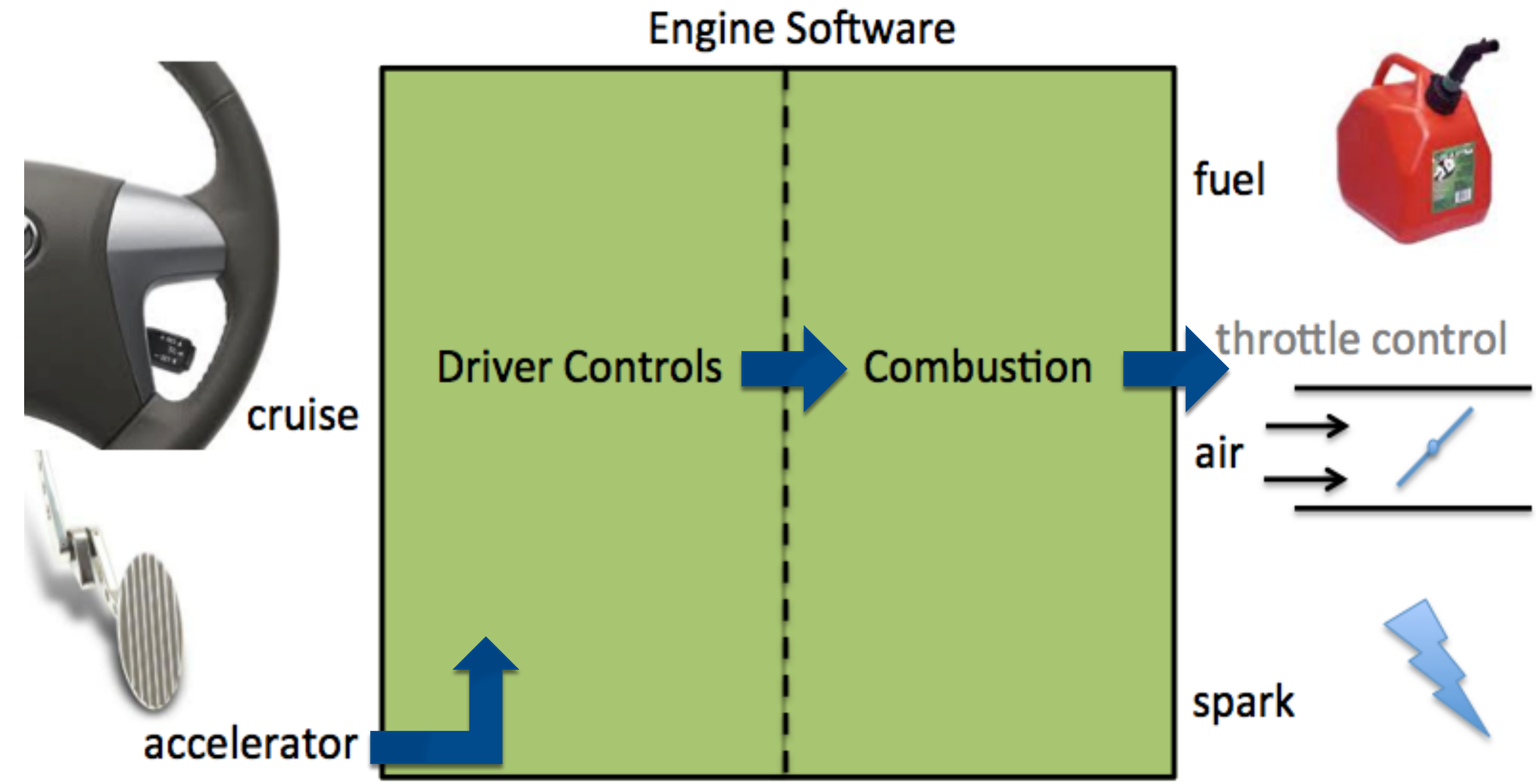
function

variable

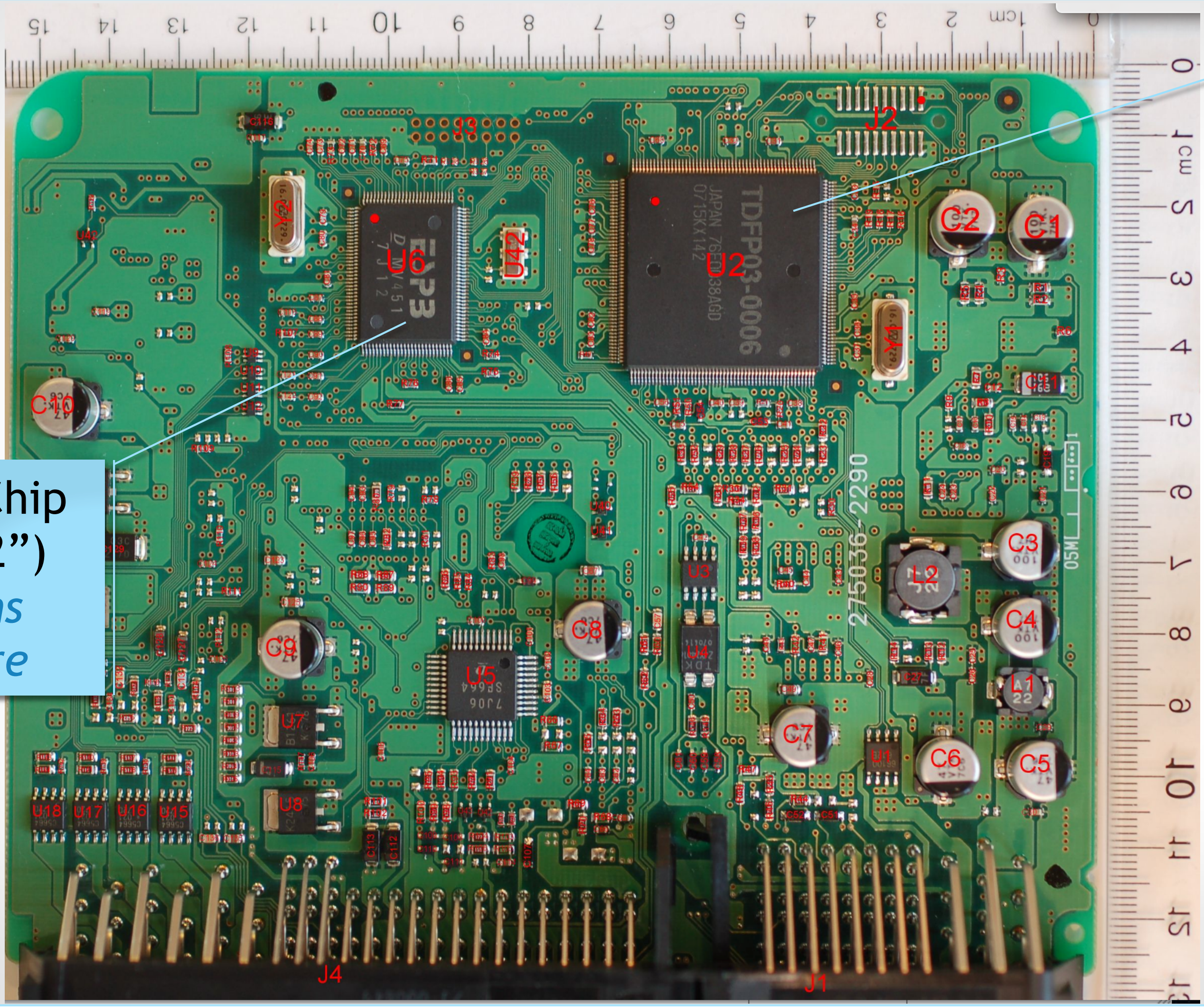
comment

```
int larger_of(int a, int b)
{
    if (a > b)
    {
        return a;      /* a contains the larger value */
    }
    else
    {
        return b;      /* b contains the larger value */
    }
}
```

ELECTRONIC THROTTLE CONTROL



TOYOTA'S ENGINE CONTROL MODULE (ECM)



Main CPU
("V850")
contains software

Monitor Chip
("ESP-B2")
contains software

SAFETY-CRITICAL SYSTEMS

Not all embedded systems can kill or injure people …

- Those that can do harm are “safety-critical systems”

What could possibly go wrong?

- A glitch in the electronics (*random hardware faults will happen*)
- A bug in the software (*any reasonably complex software has bugs*)
- An unforeseen gap in the intended safety features
- Or all three: glitch activates bug and that slips thru safety gap

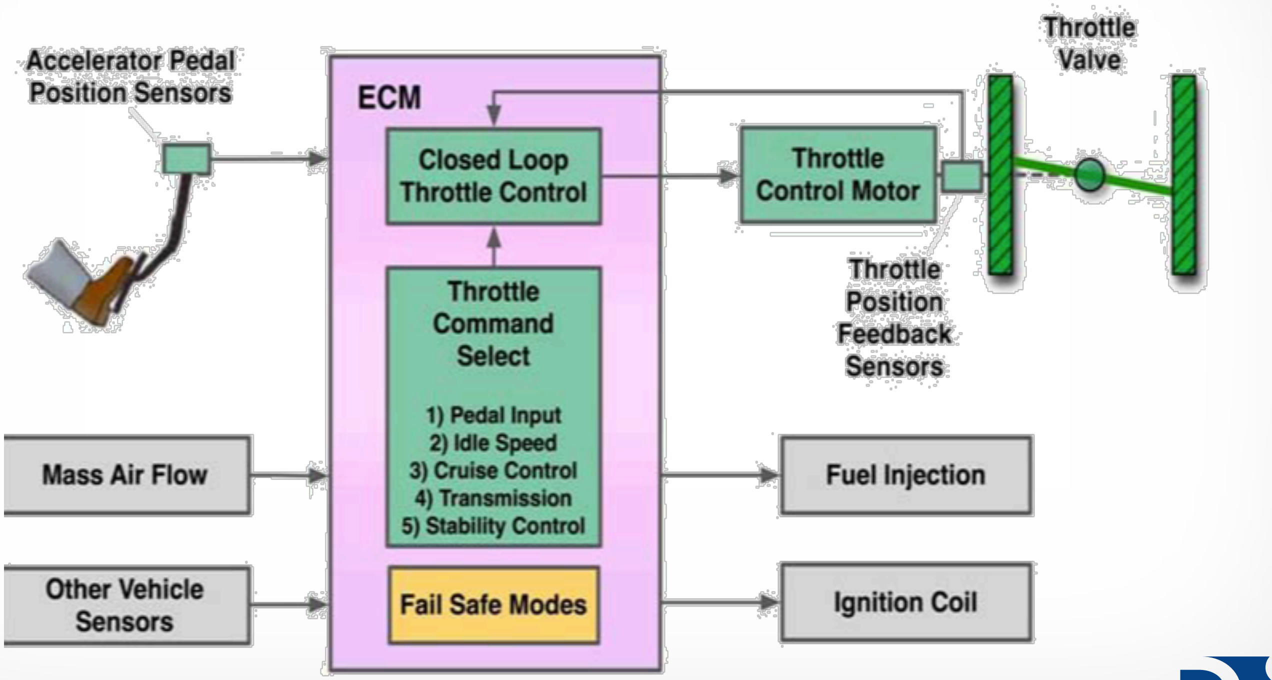
Safety cannot be an afterthought; must be designed in

- Redundancy and fault containment are key

ELECTRONIC THROTTLE CONTROL (ETCS)

"Toyota ETCS-i is an example of a safety-critical hard real-time system."

- *NASA, Appendix A, p. 118*



NASA, p. 13

SUMMARY OF 2005 CAMRY L4 CONCLUSIONS

Toyota's ETCS source code is of unreasonable quality

- Toyota's source code is defective and contains bugs

  Including bugs that can cause unintended acceleration

- Code quality metrics predict presence of additional bugs

Toyota's fail safes are defective and inadequate

- "House of cards" safety architecture

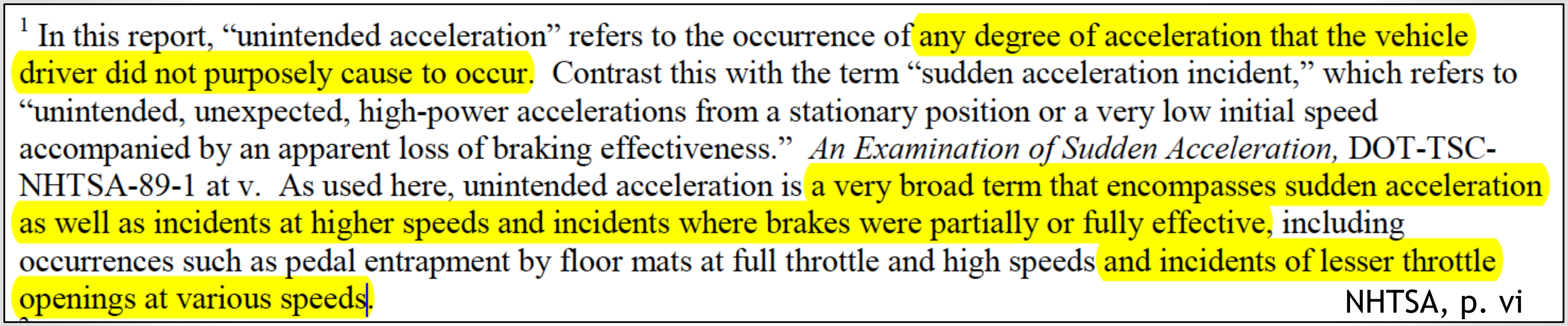
  Random hardware and software faults are a fact of life

Misbehaviors of Toyota's ETCS are a cause of UA

UNINTENDED ACCELERATION (UA)

I use the same definition as NHTSA and NASA:

- "any degree of acceleration that the vehicle driver did not purposely cause"



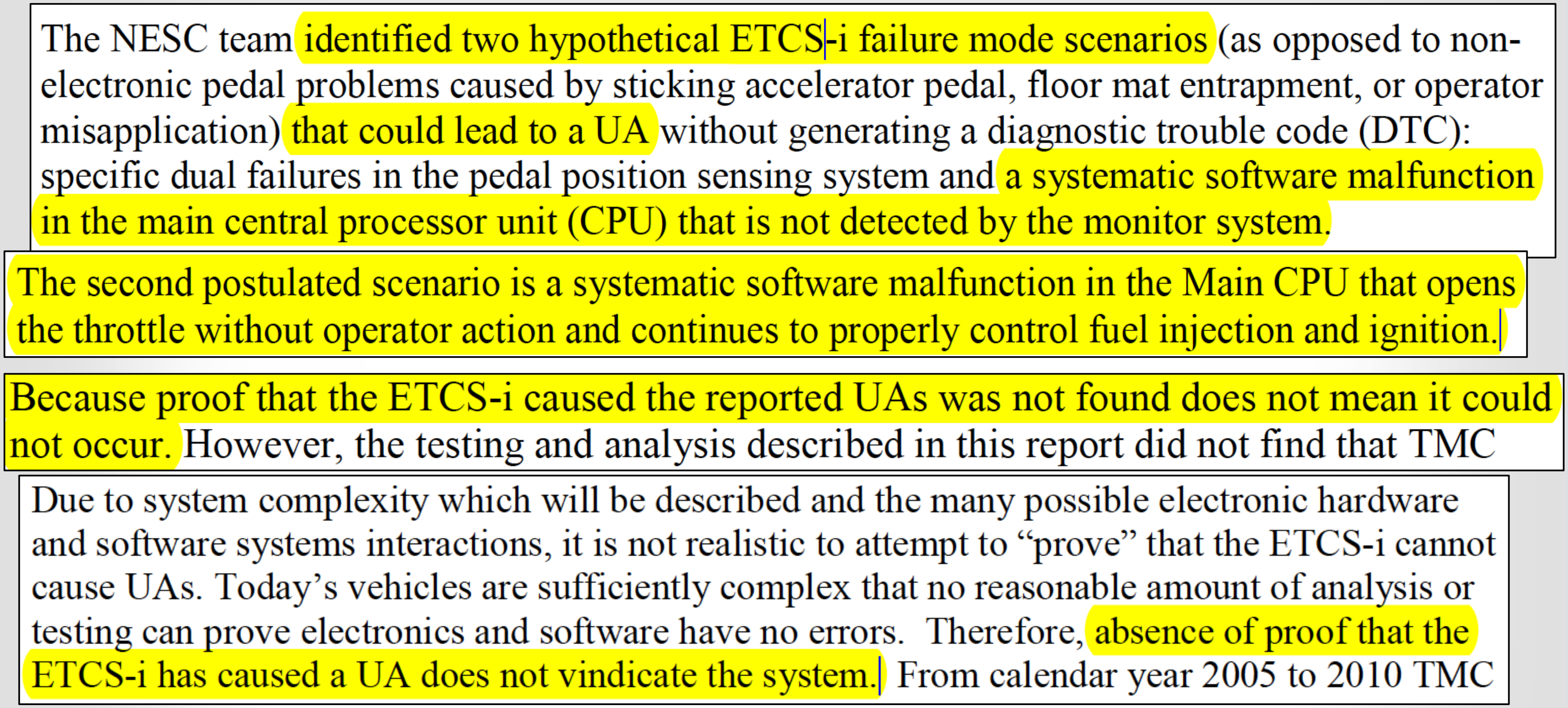
[1] In this report, "unintended acceleration" refers to the occurrence of any degree of acceleration that the vehicle driver did not purposely cause to occur. Contrast this with the term "sudden acceleration incident," which refers to "unintended, unexpected, high-power accelerations from a stationary position or a very low initial speed accompanied by an apparent loss of braking effectiveness." *An Examination of Sudden Acceleration,* DOT-TSC-NHTSA-89-1 at v. As used here, unintended acceleration is a very broad term that encompasses sudden acceleration as well as incidents at higher speeds and incidents where brakes were partially or fully effective, including occurrences such as pedal entrapment by floor mats at full throttle and high speeds and incidents of lesser throttle openings at various speeds.

NHTSA, p. vi

I also use the phrase "*loss of throttle control*"

- Throttle controls airflow, which controls engine power

NASA DID NOT RULE OUT UA BY SOFTWARE



The NESC team identified two hypothetical ETCS-i failure mode scenarios (as opposed to non-electronic pedal problems caused by sticking accelerator pedal, floor mat entrapment, or operator misapplication) that could lead to a UA without generating a diagnostic trouble code (DTC): specific dual failures in the pedal position sensing system and a systematic software malfunction in the main central processor unit (CPU) that is not detected by the monitor system.

The second postulated scenario is a systematic software malfunction in the Main CPU that opens the throttle without operator action and continues to properly control fuel injection and ignition.

Because proof that the ETCS-i caused the reported UAs was not found does not mean it could not occur. However, the testing and analysis described in this report did not find that TMC

Due to system complexity which will be described and the many possible electronic hardware and software systems interactions, it is not realistic to attempt to "prove" that the ETCS-i cannot cause UAs. Today's vehicles are sufficiently complex that no reasonable amount of analysis or testing can prove electronics and software have no errors. Therefore, absence of proof that the ETCS-i has caused a UA does not vindicate the system. From calendar year 2005 to 2010 TMC

NASA, pp.15-20

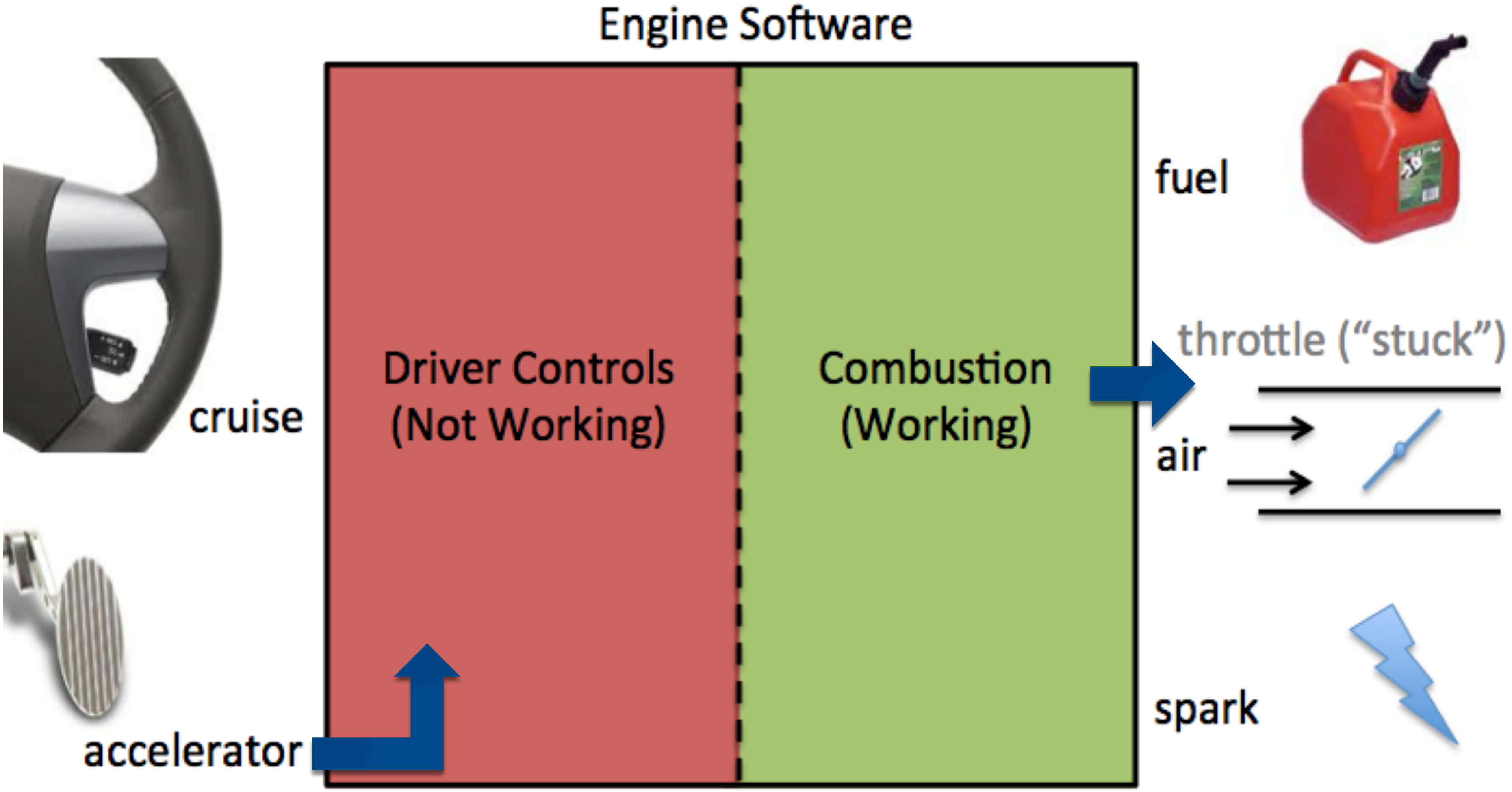
THERE ARE DEFECTS IN TOYOTA’S ETCS

2005 Camry L4 source code and in-vehicle tests confirm:

- Some critical variables are not protected from corruption
  - Mirroring was not always done
    - ➢ NASA didn’t know this (*believed mirroring was always done*)
  - No hardware protection against bit flips
    - ➢ NASA didn’t know this (*was told main CPU’s RAM had EDAC*)
- Sources of memory corruption are present
  - Stack overflow can occur
    - ➢ NASA didn’t know this (*was told stack less than half used*)
  - There are software bugs
    - ➢ NASA found bugs (*and Barr Group has found others*)

Thus Toyota’s ETCS software can malfunction …

ETCS SOFTWARE MALFUNCTION



SOFTWARE MALFUNCTIONS HAPPEN

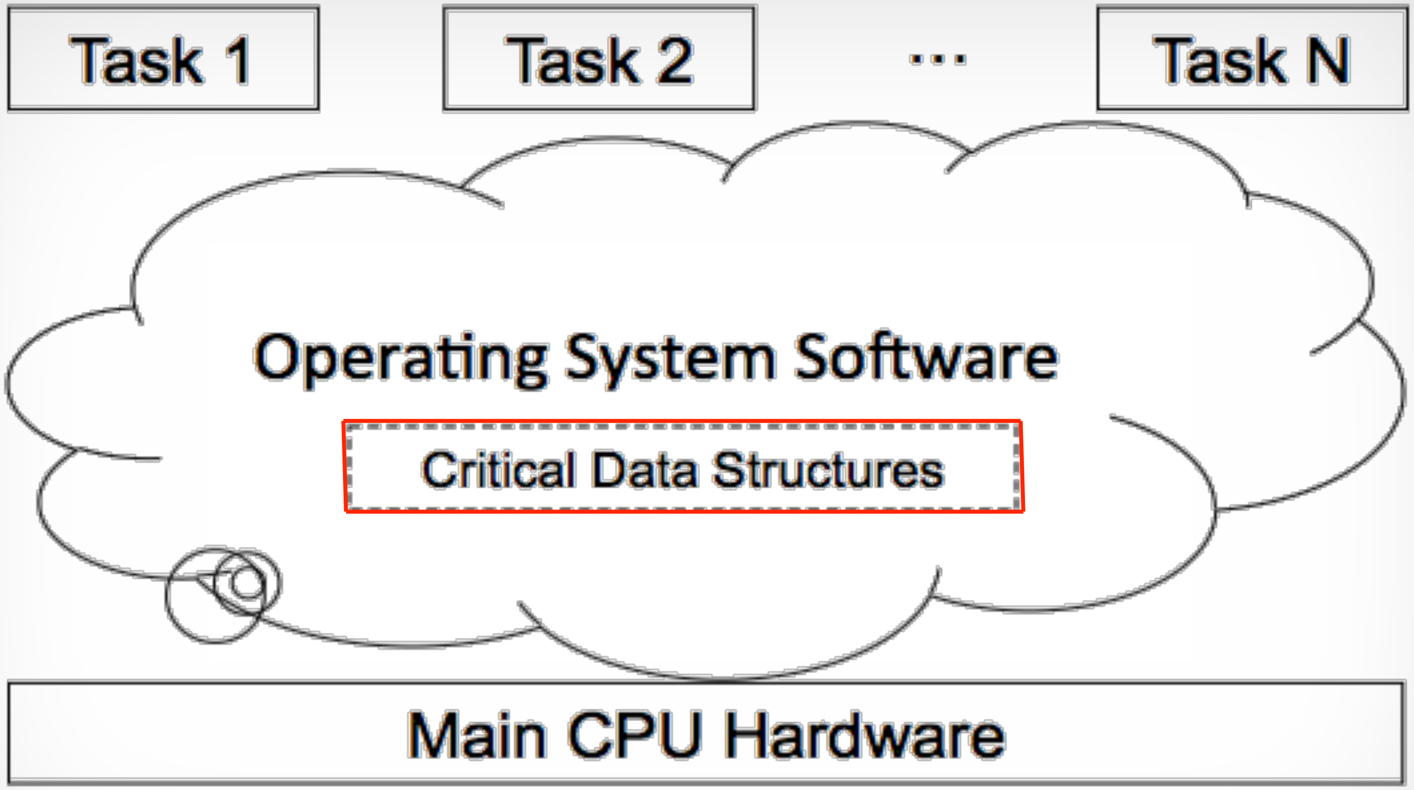
All kinds of embedded systems experience partial software malfunction from time-to-time

- e.g., most other apps working, but phone calls go direct to voice mail
- “Have you tried rebooting it?”

The 2005 Camry L4 software has a set of 24 “apps” (called “tasks”)

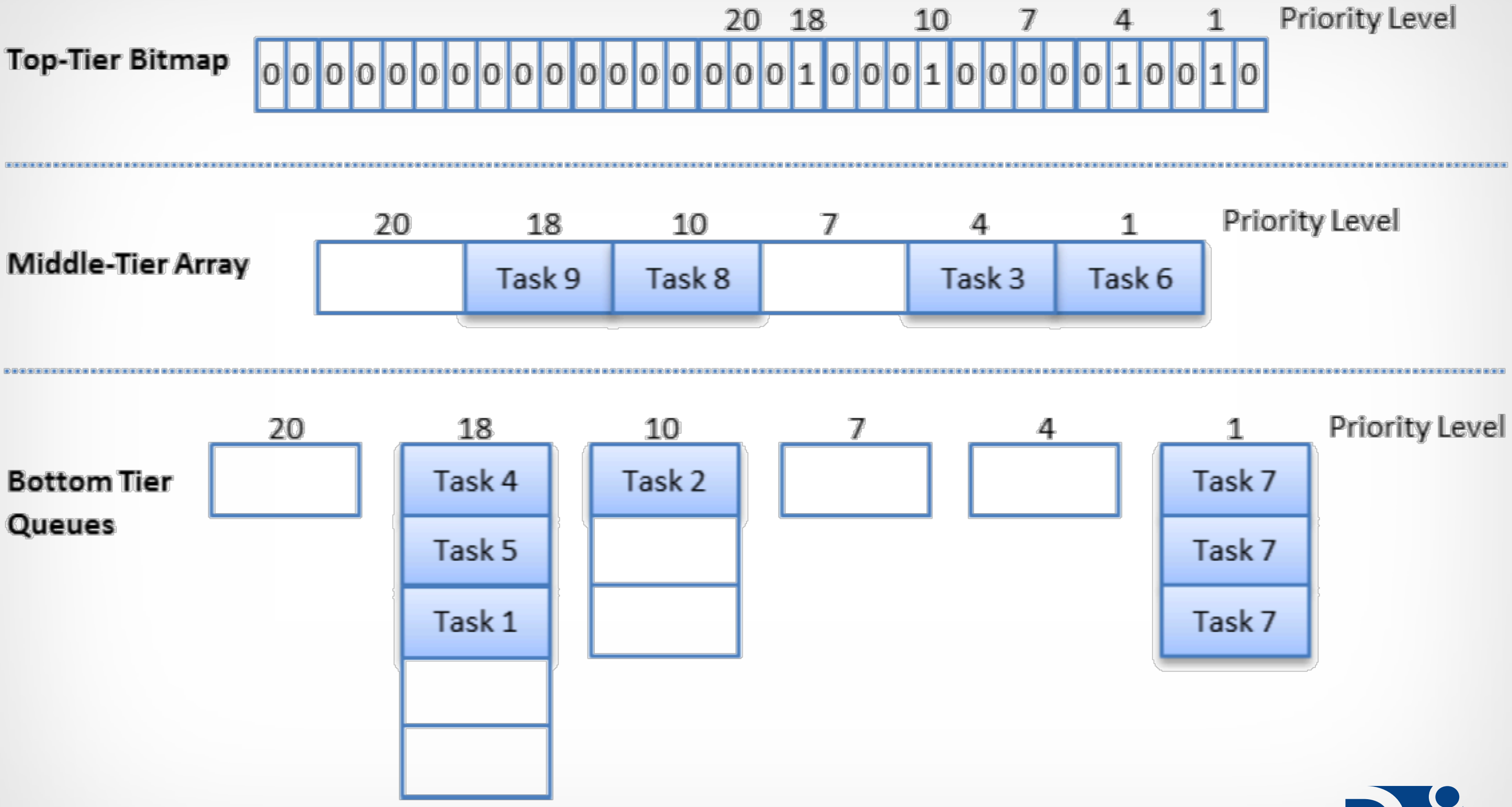
- All are meant to be running *always*

TOYOTA'S OPERATING SYSTEM (OSEK)



Barr Chapter Regarding
Toyota's Operating Systems

OSEK'S CRITICAL DATA STRUCTURES



Top-Tier Bitmap

20 18 10 7 4 1 Priority Level

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0 1 0 0 1 0

Middle-Tier Array

20 18 10 7 4 1 Priority Level

Task 9 Task 8 Task 3 Task 6

Bottom Tier Queues

20 18 10 7 4 1 Priority Level

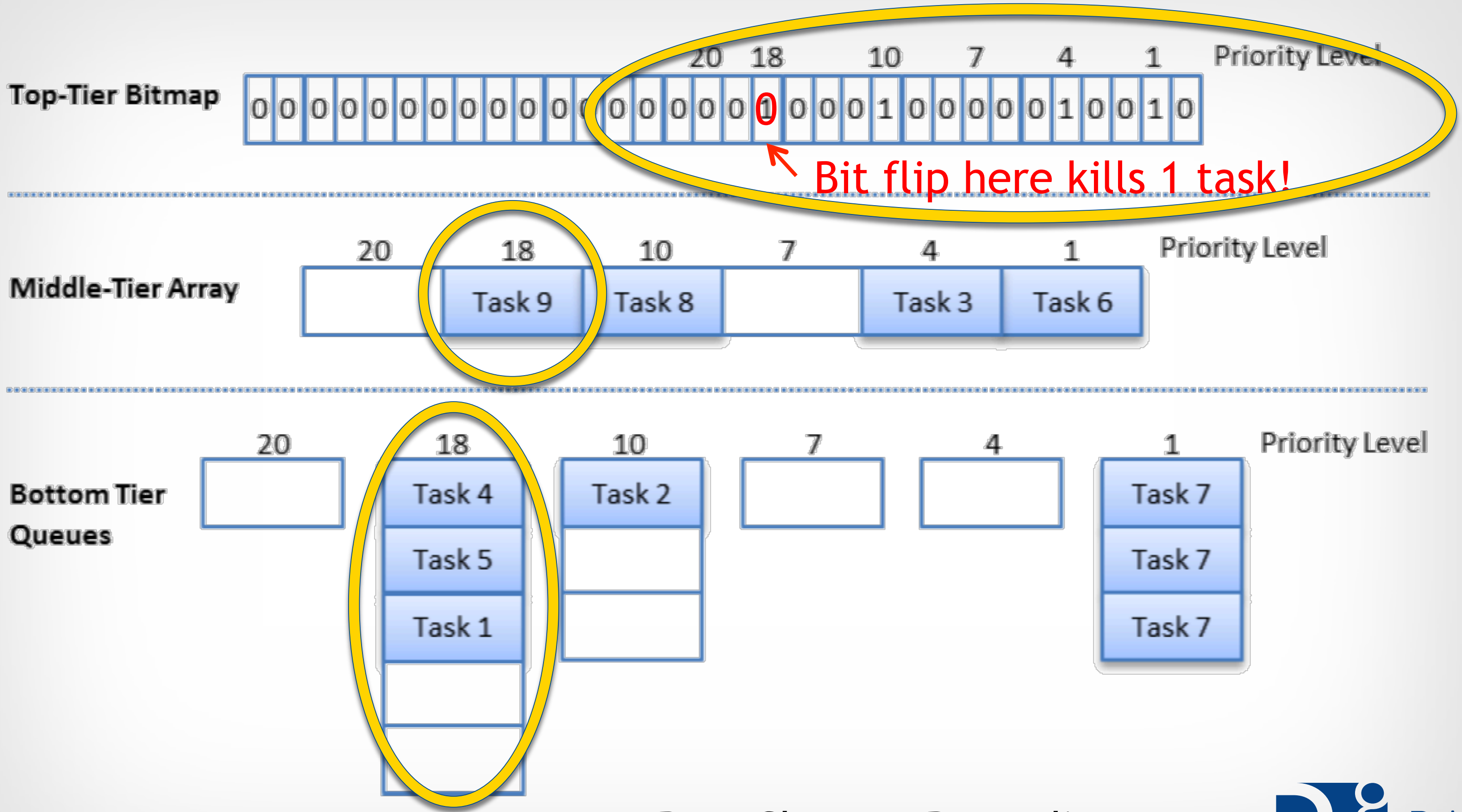
Task 4 Task 5 Task 1

Task 2

Task 7 Task 7 Task 7

Barr Chapter Regarding
Toyota's Operating Systems

MEMORY CORRUPTION AND TASK DEATH



Top-Tier Bitmap

20 18 10 7 4 1 Priority Level

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 1 0 0 1 0

Bit flip here kills 1 task!

Middle-Tier Array

20 18 10 7 4 1 Priority Level

20	18	10	7	4	1
	Task 9	Task 8		Task 3	Task 6

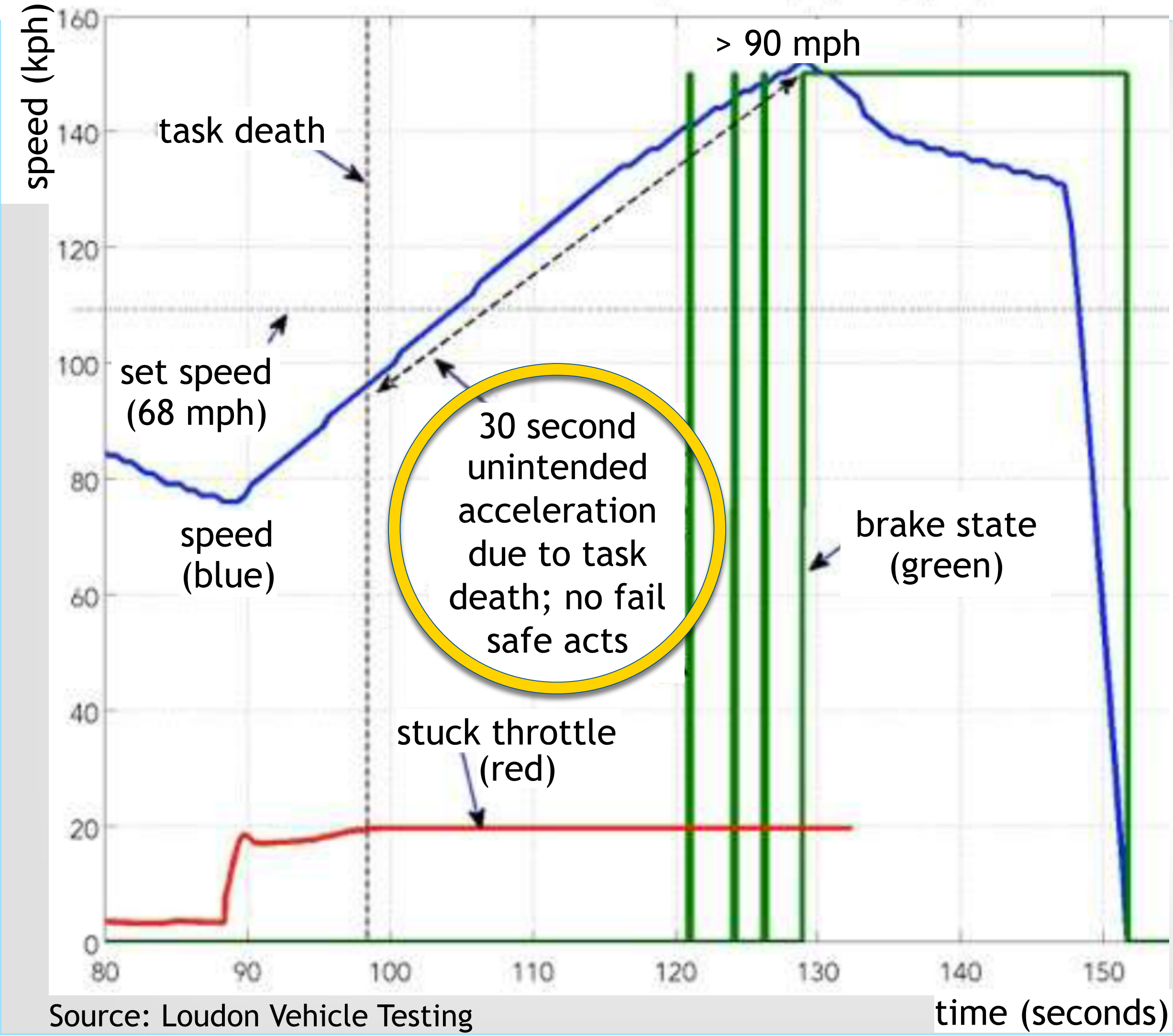
Bottom Tier Queues

20 18 10 7 4 1 Priority Level

20	18	10	7	4	1
	Task 4	Task 2			Task 7
	Task 5				Task 7
	Task 1				Task 7

Barr Chapter Regarding
Toyota's Operating Systems

EXAMPLE OF UNINTENDED ACCELERATION



Source: Loudon Vehicle Testing

- Representative of task death in real-world
- Dead task also monitors accelerator pedal, so loss of throttle control
  - ✓ Confirmed in tests
- When this task's death begins with brake press (any amount), driver must fully remove foot from brake to end UA
  - ✓ Confirmed in tests

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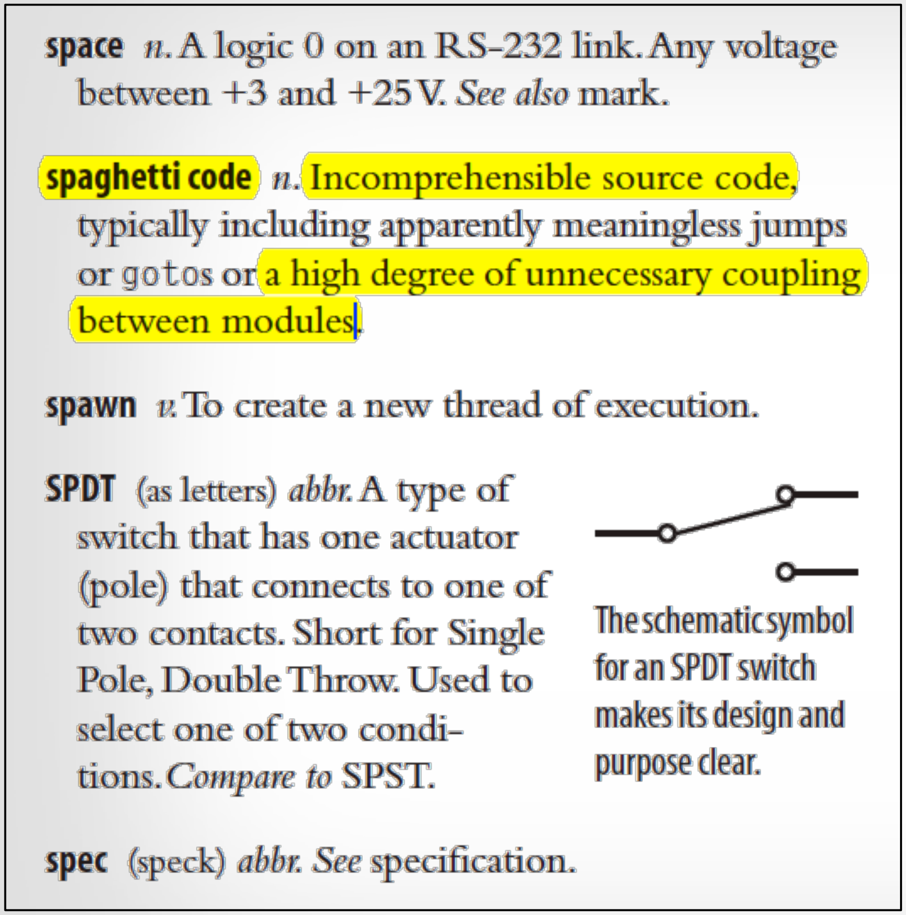
SOFTWARE CAUSES OF MEMORY CORRUPTION

Type of Software Defect	Causes Memory Corruption?	Defect in 2005 Camry L4?
Buffer Overflow	Yes	Yes
Invalid Pointer Dereference/Arithmetic	Yes	Yes
Race Condition (a.k.a., “Task Interference”)	Yes	Yes
Nested Scheduler Unlock	Yes	Yes
Unsafe Casting	Yes	Yes
Stack Overflow	Yes	Yes

SPAGHETTI CODE DEFINED



space *n.* A logic 0 on an RS-232 link. Any voltage between +3 and +25 V. *See also* mark.

spaghetti code *n.* Incomprehensible source code, typically including apparently meaningless jumps or `gotos` or a high degree of unnecessary coupling between modules.

spawn *v.* To create a new thread of execution.

SPDT (as letters) *abbr.* A type of switch that has one actuator (pole) that connects to one of two contacts. Short for Single Pole, Double Throw. Used to select one of two conditions. *Compare to* SPST.

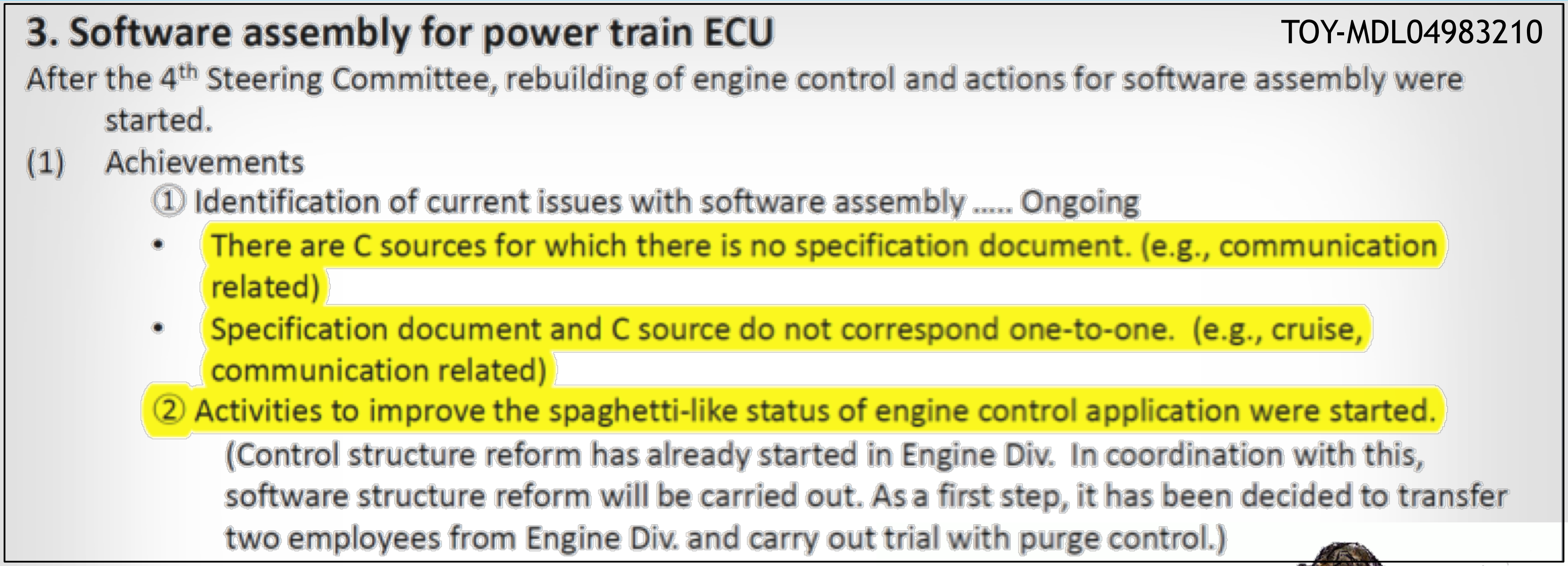
The schematic symbol for an SPDT switch makes its design and purpose clear.

spec (speck) *abbr. See* specification.

- ➢ Difficult to follow data/control paths
- ➢ Bugs likely to appear when modified
- ➢ Unnecessarily complex

Ganssle&Barr, Embedded Systems Dictionary, 2003

TOYOTA'S SPAGHETTI CODE



3. Software assembly for power train ECU

TOY-MDL04983210

After the 4th Steering Committee, rebuilding of engine control and actions for software assembly were started.

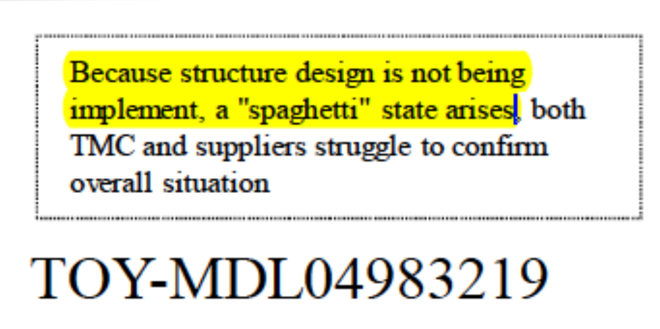
(1) Achievements

① Identification of current issues with software assembly ..... Ongoing

- There are C sources for which there is no specification document. (e.g., communication related)
- Specification document and C source do not correspond one-to-one. (e.g., cruise, communication related)

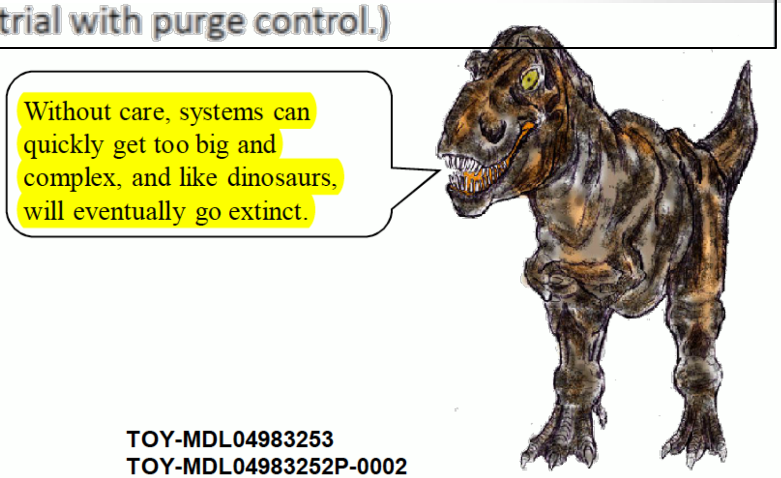
② Activities to improve the spaghetti-like status of engine control application were started.

(Control structure reform has already started in Engine Div. In coordination with this, software structure reform will be carried out. As a first step, it has been decided to transfer two employees from Engine Div. and carry out trial with purge control.)



Because structure design is not being implement, a "spaghetti" state arises, both TMC and suppliers struggle to confirm overall situation

TOY-MDL04983219



Without care, systems can quickly get too big and complex, and like dinosaurs, will eventually go extinct.

TOY-MDL04983253
TOY-MDL04983252P-0002

TYPES OF SPAGHETTI CODE

Data-flow spaghetti

- Complex coupling between software modules and between tasks
- Count of global variables is a software metric for “tangledness”

  2005 Camry L4 has >11,000 global variables (NASA)

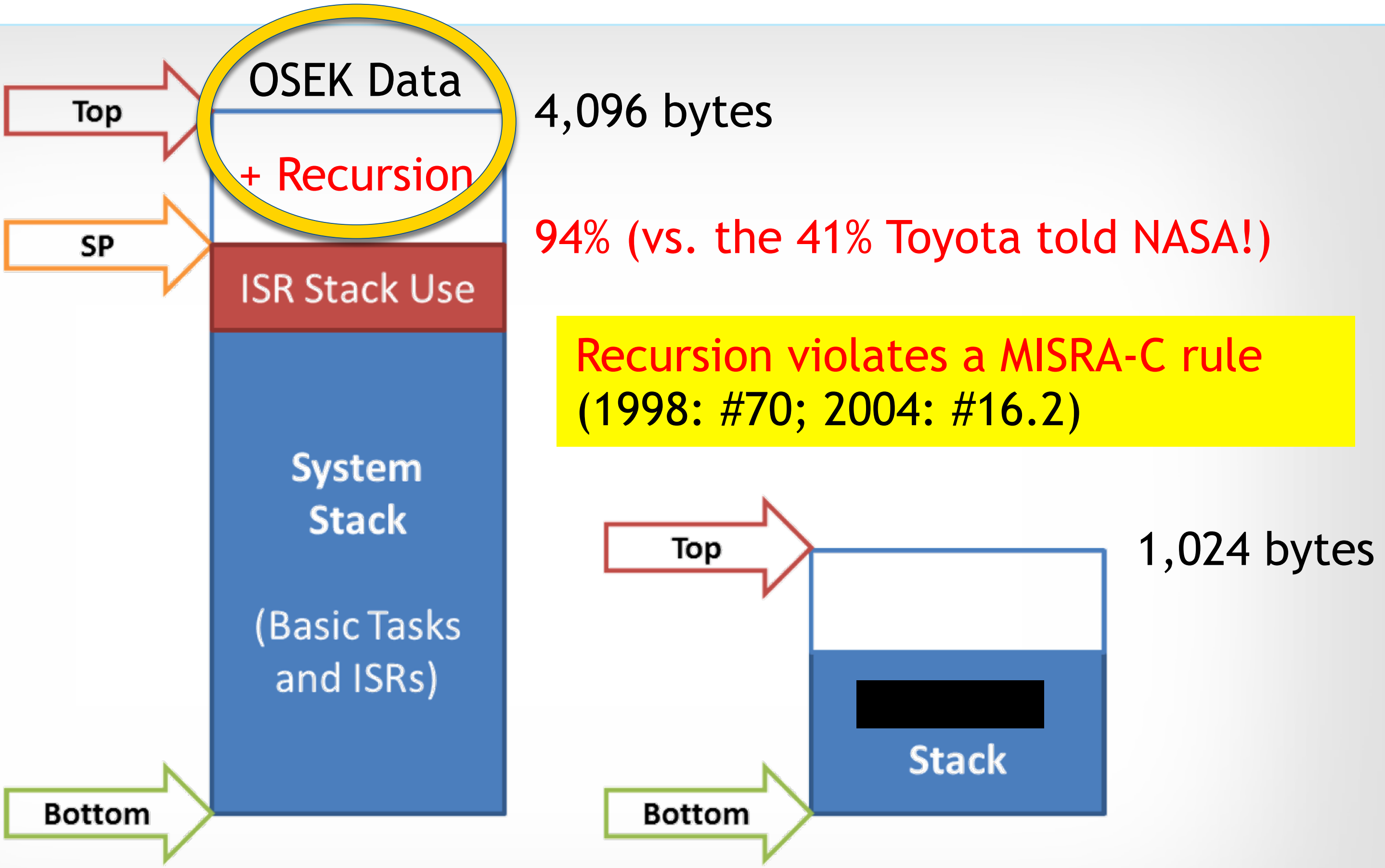
Control-flow spaghetti

- Many long, overly-complex function bodies
- Cyclomatic Complexity is a software metric for “testability”

  2005 Camry L4 has 67 functions scoring >50 (“untestable”)

  The throttle angle function scored over 100 (unmaintainable)

STACK ANALYSIS FOR 2005 CAMRY L4



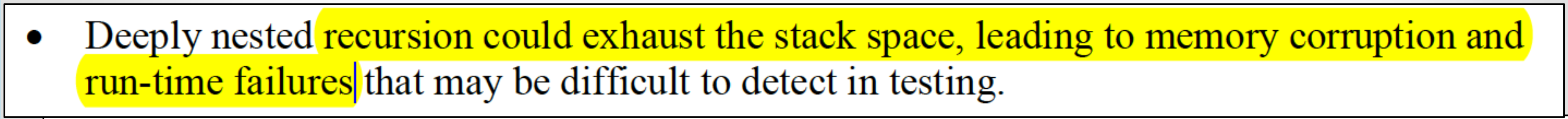
94% (vs. the 41% Toyota told NASA!)

Recursion violates a MISRA-C rule
(1998: #70; 2004: #16.2)

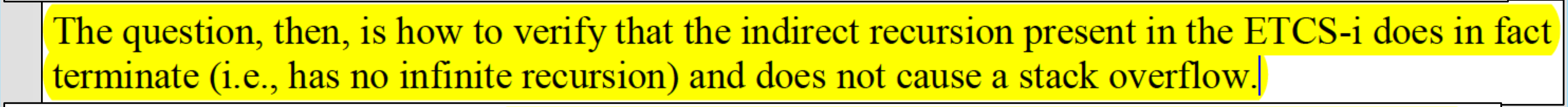
Barr Chapter Regarding
Toyota’s Stack Analysis

NASA'S VIEW ON RECURSION

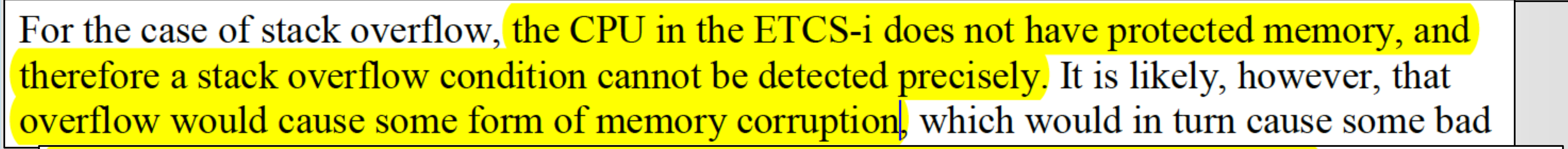
NASA was concerned about possible stack overflow…



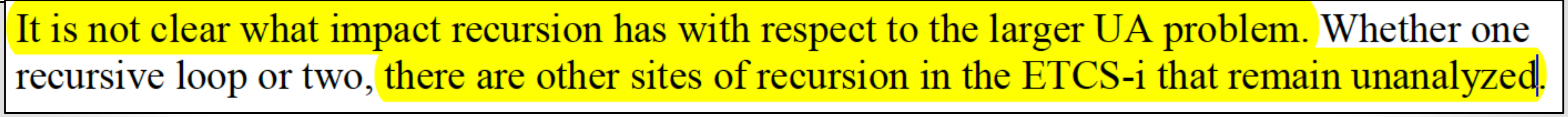
- Deeply nested recursion could exhaust the stack space, leading to memory corruption and run-time failures that may be difficult to detect in testing.



The question, then, is how to verify that the indirect recursion present in the ETCS-i does in fact terminate (i.e., has no infinite recursion) and does not cause a stack overflow.

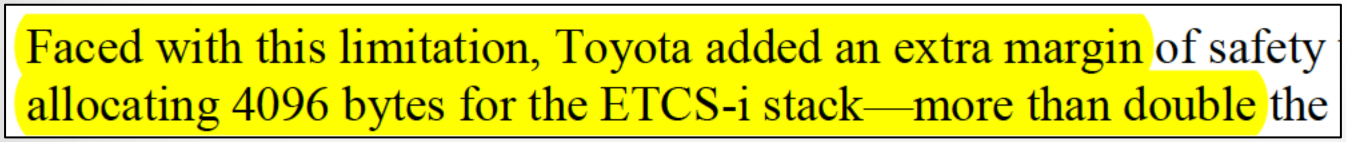


For the case of stack overflow, the CPU in the ETCS-i does not have protected memory, and therefore a stack overflow condition cannot be detected precisely. It is likely, however, that overflow would cause some form of memory corruption, which would in turn cause some bad



It is not clear what impact recursion has with respect to the larger UA problem. Whether one recursive loop or two, there are other sites of recursion in the ETCS-i that remain unanalyzed.

… and NASA didn't know there was so little safety margin!



Faced with this limitation, Toyota added an extra margin of safety allocating 4096 bytes for the ETCS-i stack—more than double the

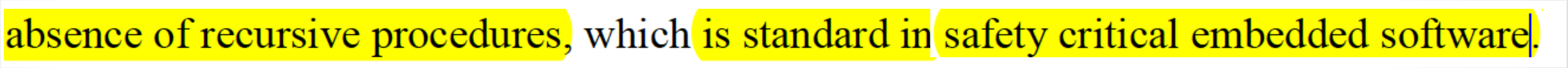
NASA, Appendix A, pp. 20, 129-134

TOYOTA’S MAJOR STACK MISTAKES

Toyota botched its worst-case stack depth analysis

- Missed function calls via pointers (*failure to automate*)
- Didn’t include any stack use by library and assembly functions
  - Approximately 350 functions ignored
- HUGE: Forgot to consider OS stack use for context switching!

On top of that… Toyota used dangerous recursion



absence of recursive procedures, which is standard in safety critical embedded software.

And… Toyota failed to perform **run-time stack monitoring**

- A safety check that the cheaper 2005 Corolla ECM had!

TOYOTA FAILED TO COMPLY WITH STANDARDS
Operating System Standards

"OSEK" is an international standard API

- Specifically designed for use in automotive software
- Multiple suppliers of OSEK operating systems
- Compliance tests ensure compatibility across versions

But Toyota's Rx-OSEK850 version is non-standard!!!

- Was not certified as OSEK compliant
- Certified products for V850 were available by 2002

TOYOTA FAILED TO COMPLY WITH STANDARDS
Automotive Industry Coding Guidelines

MISRA-C – motor industry software reliability coding rules for C

- By 2004, “*the successes and global use of MISRA-C across automotive, aerospace, medical, and other industries has been staggering.*”
- *“In Japan, we have worked with representatives of JSAE, JAMA, …”*

From 2002-2004, Toyota said in public they followed MISRA-C

- But NASA reported > 7,000 violations of *some* of the rules (p. 29)
- I checked the full set and found > 80,000 in violations in 2005 Camry L4

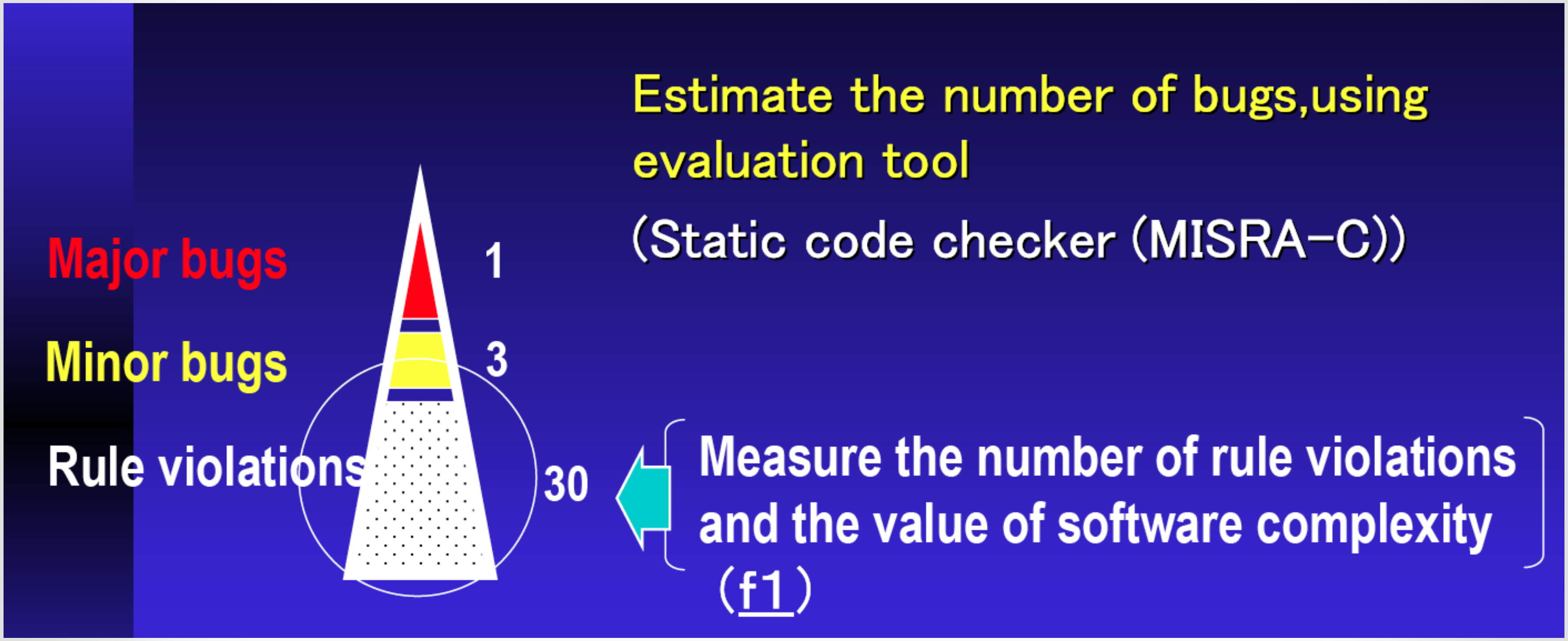
Toyota’s coding standard only has 11 MISRA-C rules

- And 5 of those are violated in the actual source code

Barr Chapter Regarding
Toyota’s MISRA-C Violations

VIOLATING CODING RULES CAUSES BUGS

In the words of Toyota itself:



Estimate the number of bugs,using evaluation tool

(Static code checker (MISRA-C))

Measure the number of rule violations and the value of software complexity

(f1)

VANALFEN006972 (Kawana, 2004)

TOYOTA FAILED TO COMPLY WITH STANDARDS
Internal Coding Standards

Toyota maintains a set of company internal coding rules

- Specifically for “power train” ECM software developers to follow
  - Mr. Ishii’s statement about 50% MISRA-C overlap was found false
- NASA reported Toyota didn’t follow *some* of its rules (p. 22)
  - I found at least 32% of Toyota’s coding rules were violated

Enforcement is the most important part of having a rule

- Demonstrates lack of engineering discipline at Toyota
- Part of a larger pattern of inadequate software process/oversight
  - Inadequate and untracked peer code reviews
  - No bug-tracking system

TOYOTA ADMITS ETCS HAS SOFTWARE BUGS

A: ***When it comes to software, there are going to be bugs, and [that] is the case not just with Toyota but with [any] software in the automotive industry and any software. So the issue is not whether or not there is a bug but rather is the bug an important material bug.***

– *Ishii 5/24/12 Deposition, p. 91*

Indeed there are bugs, including "important material bugs"

NASA'S SOFTWARE AREAS OF CONCERN

NASA, Appendix B, pp. 36-39

○ = Defects Found by Barr Group

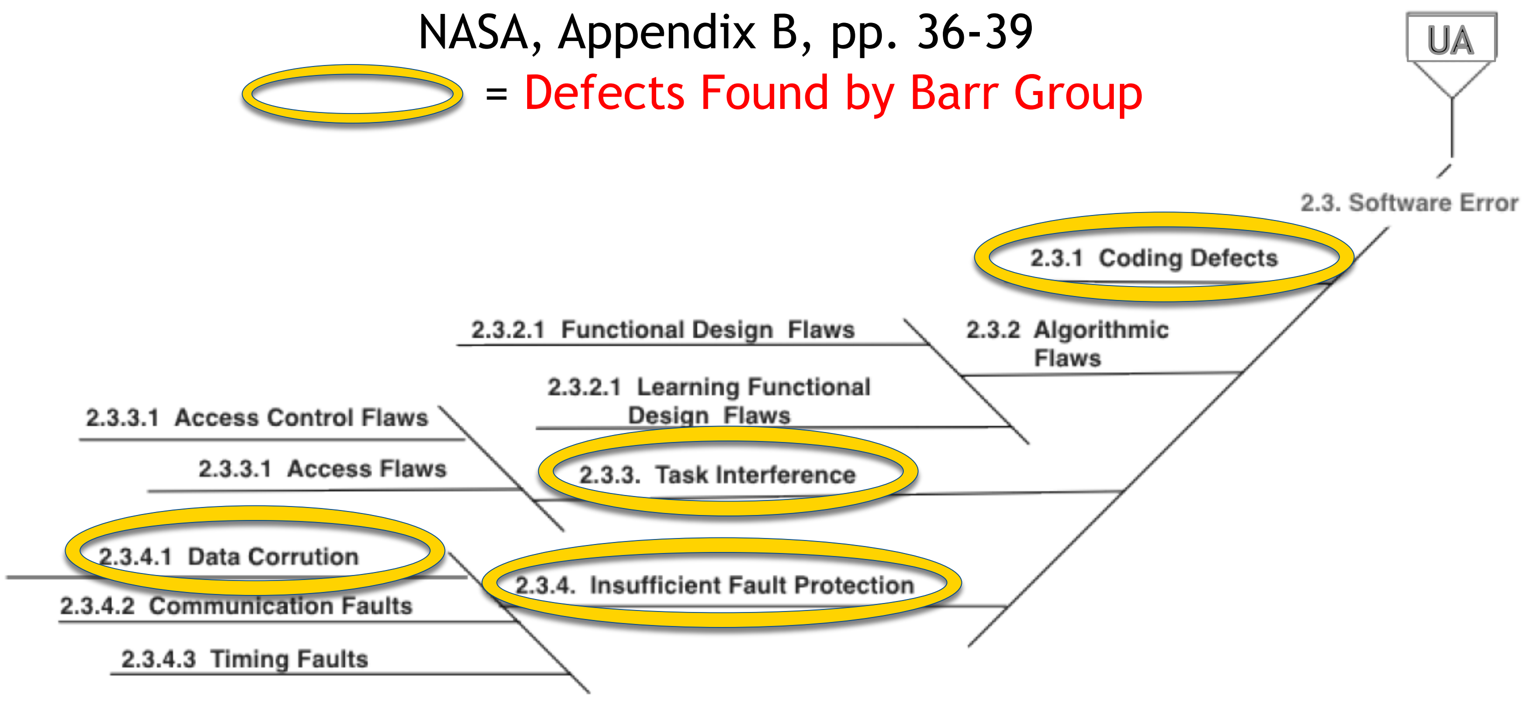

UA
2.3. Software Error
2.3.1 Coding Defects
2.3.2.1 Functional Design Flaws
2.3.2 Algorithmic Flaws
2.3.2.1 Learning Functional Design Flaws
2.3.3.1 Access Control Flaws
2.3.3.1 Access Flaws
2.3.3. Task Interference
2.3.4.1 Data Corrution
2.3.4. Insufficient Fault Protection
2.3.4.2 Communication Faults
2.3.4.3 Timing Faults

Figure B7-1. Software Error Fishbone Diagram

Barr Chapter Regarding
Task Death and UA

TOYOTA’S DEFECTIVE “SAFETY LAYERS”

Layer 1	Mirroring of Critical Variables	Barr Chapter Regarding Toyota’s Memory Protections
Layer 2	DTCs and Fail-Safe Modes	Barr Chapter Regarding Toyota’s Fail-Safe Modes
Layer 3	Watchdog Supervisor	Barr Chapter Regarding Toyota’s Watchdog Supervisor
Layer 4	ESP-B2 Monitor CPU	Barr Chapter Regarding Toyota’s Monitor CPU

LAYER 1: MIRRORING OF CRITICAL VARIABLES

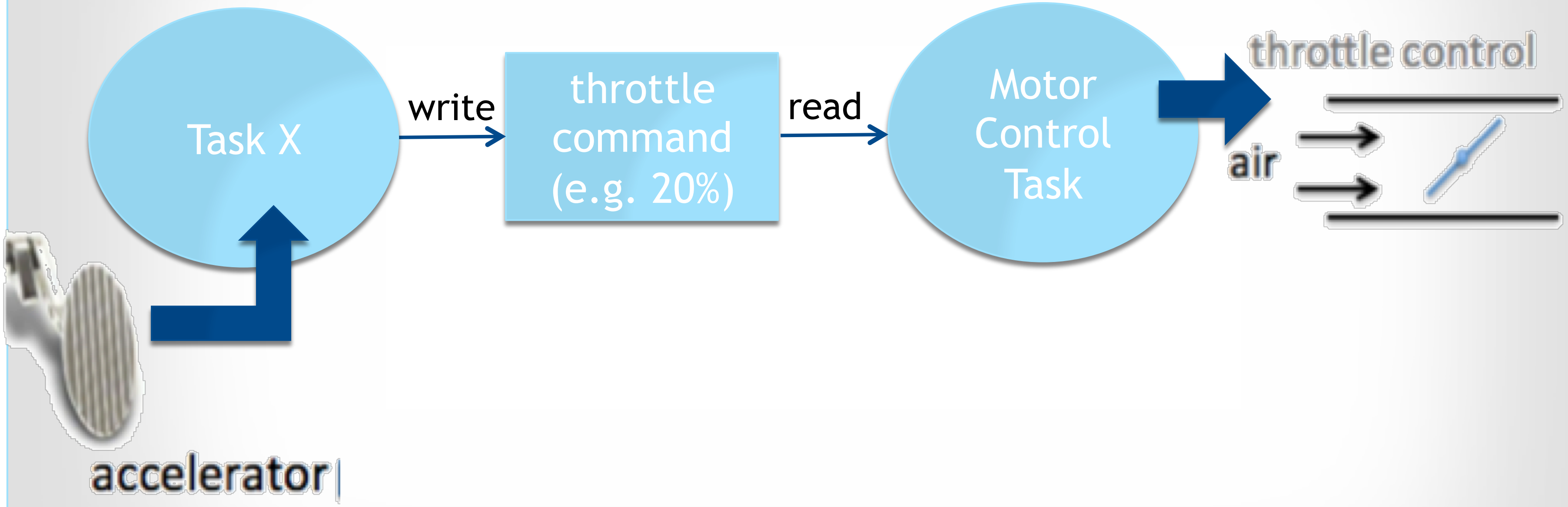
Toyota's engineers sought to protect numerous variables against software- and hardware-caused corruptions

- e.g., by "mirroring" their contents in a 2nd location

But FAILED TO MIRROR several key critical variables

- OSEK's critical internal data structures
- THE *target throttle angle* global variable!
  - Commands a part of the software to open the throttle
    - Recalculated every 8 ms (when the tasks are all alive)
  - **Corruption is indistinguishable from a driver gas pedal press!**

THROTTLE COMMAND DESIGN



Barr Chapter Regarding
Toyota's Software Architecture

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UA VIA MEMORY CORRUPTION

Task X death causes loss of throttle control by driver

- Changes at the accelerator pedal have no effect on throttle angle
- Cruise control switches have no effect

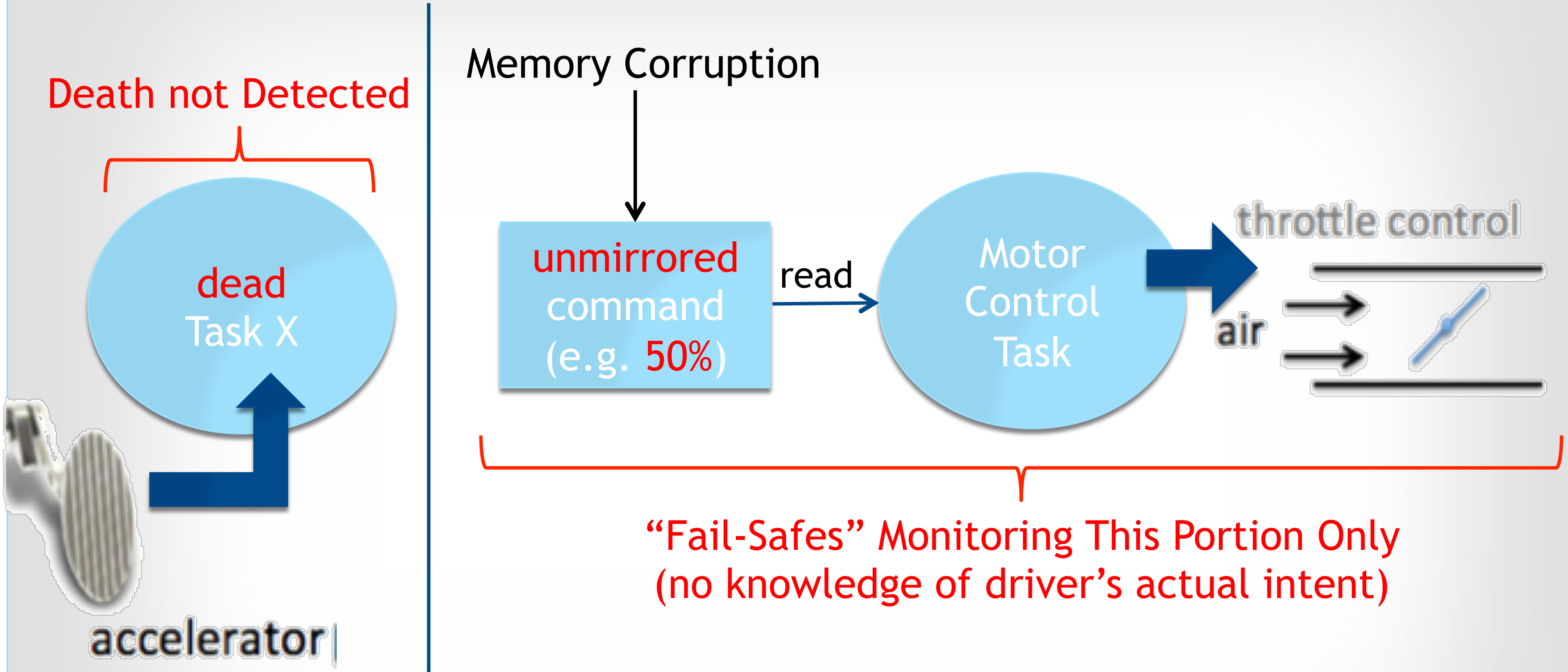
Motor Control Task continues to drive throttle motor; engine powered

- Throttle could stick at last computed *throttle command*, or
- Change angle via corruption of *throttle command* global variable

One corruption event can cause task death <u>and</u> open throttle

- Memory corruptions are like ricocheting bullets

TOYOTA'S DEFECTIVE THROTTLE CONTROL



"Fail-Safes" Monitoring This Portion Only
(no knowledge of driver's actual intent)

Barr Chapter Regarding
Toyota's Software Bugs

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LAYER 2: DTCs AND FAIL-SAFE MODES

NASA talks about 5 fail-safe modes (pp. 79-83)

- Limp home modes 1-3 (*degrees of gas pedal sensor mistrust*)
- Idle mode fuel cut (*2,500 rpm limit at idle*)
- Engine off (*via several different "class 2" failures*)

However, all 5 fail-safes are in same Task X

- Throttle control and fail-safes in same fault containment region
  - Unreasonable design; alternative structures well-known

Most diagnostic trouble codes need Task X too!

Barr Chapter Regarding
Toyota's Fail Safe Modes

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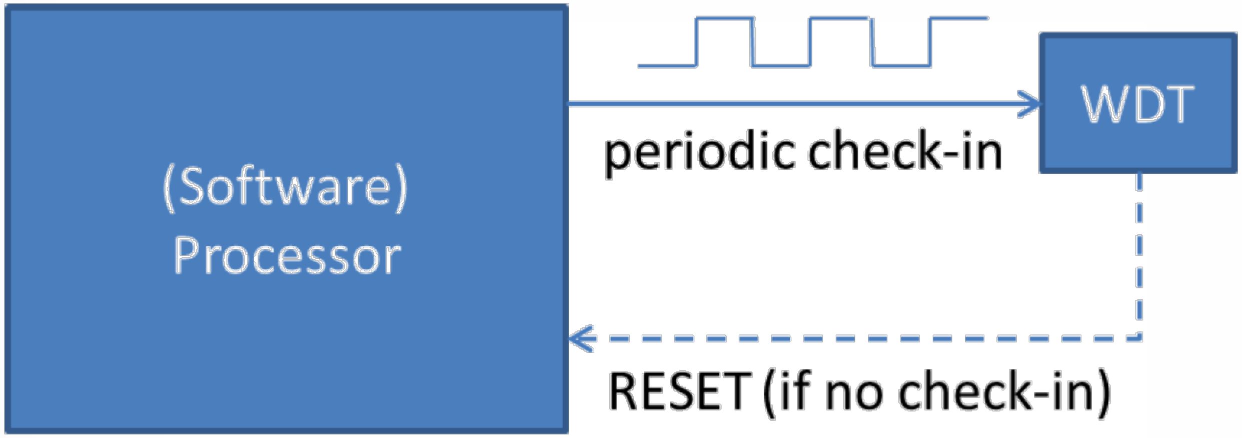
LAYER 3: WATCHDOG SUPERVISOR

A "watchdog timer" is hardware to auto-reset software

- Healthy software should periodically "check-in" to prevent reset



With multiple tasks, health of all tasks must be checked

Barr Chapter Regarding
Toyota's Watchdog Supervisor

TOYOTA'S DEFECTIVE WATCHDOG DESIGN

Toyota's watchdog supervisor design is unreasonable

- Incapable, ever, of detecting death of majority of tasks
- Incapable of properly and reliably detecting *CPU overload*
- Allows vehicle misbehavior due to overloads lasting up to 1.5s
- Resets the watchdog timer hardware in a timer tick ISR
- Explicitly ignores and discards most operating system error codes

  Ignoring error codes violates a MISRA-C rule (1998: #86; 2004: #16.10)

Reasonable design alternatives were well known

- Indeed the primary purpose should've been to detect task death
- 2005 Prius (HV-ECU) watchdog is better

Barr Chapter Regarding
Toyota's Watchdog Supervisor

LAYER 4: ESP-B2 MONITOR CPU

“System Guards”

- All (3) useless after Task X death (don’t know driver intent)

“Brake Echo Check”

- Depends on the driver to take action—after UA has already begun!

  Sometimes a counter-intuitive/dangerous action

  - ➢ Clearly this is not a “designed” fail-safe for UA or task death
- Takes the wrong actions (*should’ve reset ECM not stalled car*)
- Not 100% reliable

Does not detect all main CPU malfunctions

TOYOTA FAILED TO REVIEW MONITOR CPU

A: ***With respect to [the monitor CPU], the development process is completely different. When it comes to the source code that would be embedded in [the monitor CPUs] we, Toyota, don't receive them. … there would not be a design review done on the software.***

Q: *Now, the monitoring software for the electronic throttle control system is in the [] ESP-B2 chip; correct?*

A: ***Yes.***

- Ishii 5/24/12 Deposition, pp. 36-37

AGAIN: FAILED TO REVIEW MONITOR CPU!

The critical “monitor CPU” that checks the main CPU has never been independently reviewed

- Toyota doesn’t even have a copy of the source code
- NASA didn’t review that critical system component either
  - ESP-B2 source code was not provided to NASA

!?

Barr Group has reviewed Denso’s ESP-B2 source code

- Monitor CPU for 2005-2009 Camry L4 (and some other models)

MONITOR CPU IS LAST LINE OF UA DEFENSE

But ESP-B2 monitor CPU could have included a proper UA defense:

- **IF (driver is braking & throttle is not closing) THEN reset ECM**
  - *Something is not right with the main CPU when that happens!*
  - Resets of main CPU barely noticeable at speed (brief rpm drop)
- CRITICAL to ending UA in vehicles with potential vacuum loss

Per car cost to add this safety feature is $0.00 (it's just bits)

- There was enough memory and CPU bandwidth for these instructions
- All of the required electrical inputs and outputs were already present
- In line with E-Gas Level 3 recommendations

TOYOTA'S DEFECTIVE SOFTWARE PROCESS

FMEA was incomplete; single points of failure are present

- Because: Toyota didn't adopt a formal safety process

Peer reviews not done on OS code and ESP-B2 code

- Because: Toyota didn't perform code reviews; used non-standard OSEK

Toyota's own "power train" coding standard not enforced

- Because: Toyota didn't follow through with software suppliers

Watchdog supervisor doesn't detect most task's deaths

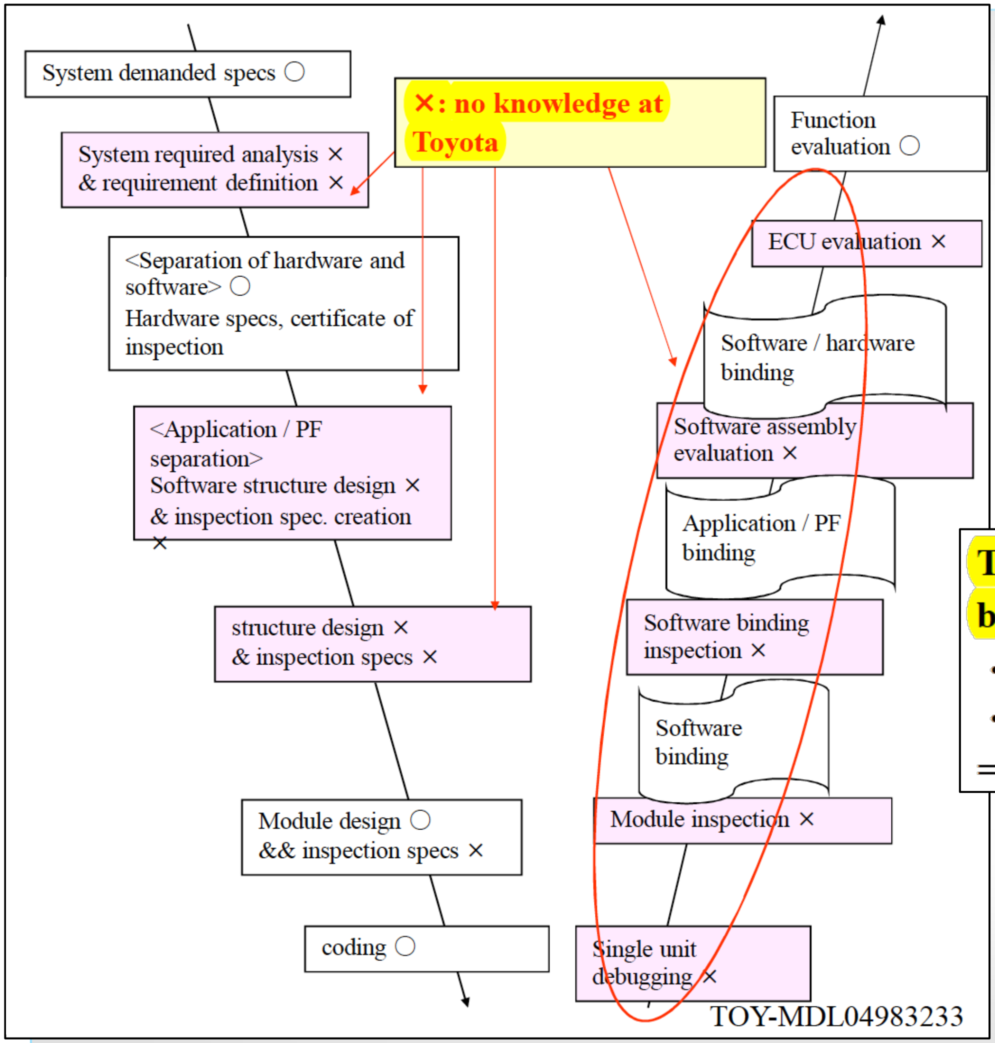
- Generally costs less to push the limits than upgrade to faster CPU

No EDAC protection against hardware bit flips

- Generally costs less to make memory chips without EDAC

If confident, why let NASA believe there was EDAC?

TOYOTA'S INADEQUATE SOFTWARE PROCESS



×: no knowledge at Toyota

System demanded specs ○

System required analysis ×
& requirement definition ×

<Separation of hardware and software> ○
Hardware specs, certificate of inspection

<Application / PF separation>
Software structure design ×
& inspection spec. creation ×

structure design ×
& inspection specs ×

Module design ○
&& inspection specs ×

coding ○

Function evaluation ○

ECU evaluation ×

Software / hardware binding

Software assembly evaluation ×

Application / PF binding

Software binding inspection ×

Software binding

Module inspection ×

Single unit debugging ×

TOY-MDL04983233

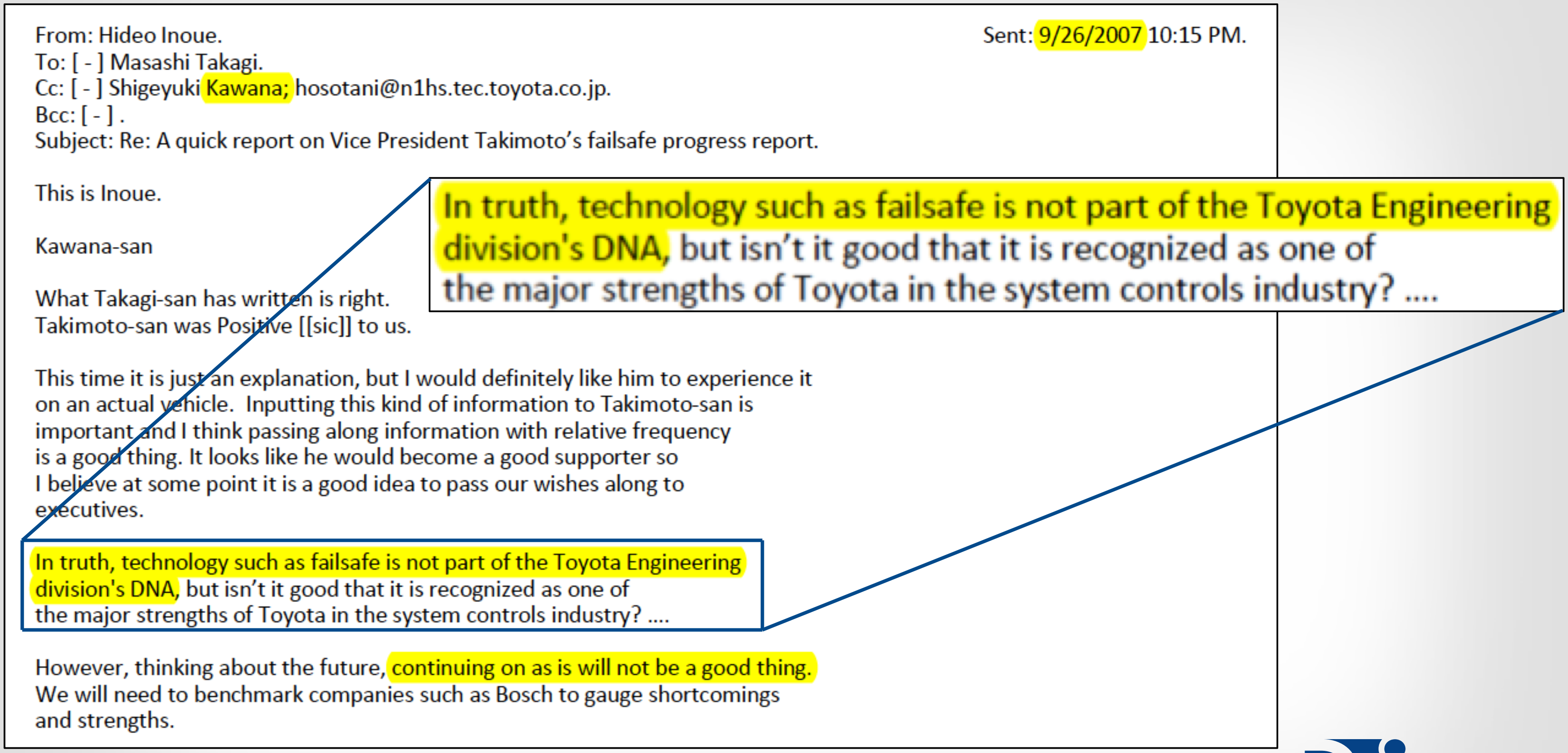
- ➢ Toyota failed to exercise a safe standard of care for software
  - ➢ Relied too much on vendors
  - ➢ Lacked internal expertise
- ➢ Inadequate supervision and training of software

There is a process in place for hardware, but not software.

- Process IN/OUT, timeframe not decided.
- There are processes at Toyota yielding no knowledge.

⇒ Large deviation in product quality among vendors.

TOYOTA’S DEFECTIVE SAFETY CULTURE



From: Hideo Inoue.
To: [-] Masashi Takagi.
Cc: [-] Shigeyuki Kawana; hosotani@n1hs.tec.toyota.co.jp.
Bcc: [-] .
Subject: Re: A quick report on Vice President Takimoto’s failsafe progress report.

Sent: 9/26/2007 10:15 PM.

This is Inoue.

Kawana-san

What Takagi-san has written is right.
Takimoto-san was Positive [[sic]] to us.

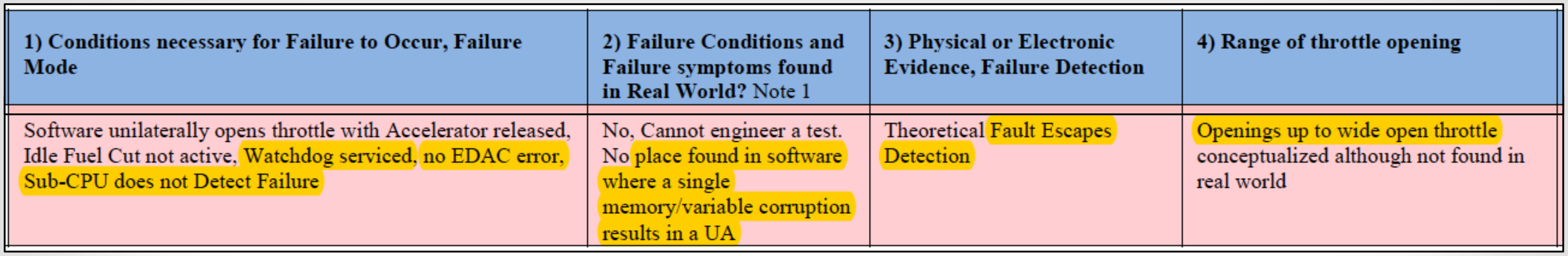
This time it is just an explanation, but I would definitely like him to experience it on an actual vehicle. Inputting this kind of information to Takimoto-san is important and I think passing along information with relative frequency is a good thing. It looks like he would become a good supporter so I believe at some point it is a good idea to pass our wishes along to executives.

In truth, technology such as failsafe is not part of the Toyota Engineering division's DNA, but isn’t it good that it is recognized as one of the major strengths of Toyota in the system controls industry? ....

However, thinking about the future, continuing on as is will not be a good thing. We will need to benchmark companies such as Bosch to gauge shortcomings and strengths.

In truth, technology such as failsafe is not part of the Toyota Engineering division's DNA, but isn’t it good that it is recognized as one of the major strengths of Toyota in the system controls industry? ....

NASA SOUGHT WHAT BARR GROUP FOUND



1) Conditions necessary for Failure to Occur, Failure Mode	2) Failure Conditions and Failure symptoms found in Real World? Note 1	3) Physical or Electronic Evidence, Failure Detection	4) Range of throttle opening
Software unilaterally opens throttle with Accelerator released, Idle Fuel Cut not active, Watchdog serviced, no EDAC error, Sub-CPU does not Detect Failure	No, Cannot engineer a test. No place found in software where a single memory/variable corruption results in a UA	Theoretical Fault Escapes Detection	Openings up to wide open throttle conceptualized although not found in real world

NASA p. 78

"Single memory corruption results in UA"

"Fault escapes detection"

- "No EDAC error" (*because there is no EDAC!*)
- "Idle fuel cut not active" (*because in same task*)
- "Watchdog serviced" (*because defective design*)
- Monitor-CPU "does not detect failure" (*because not designed to*)

"Openings up to wide open throttle"

UNREASONABLE SINGLE POINTS OF FAILURE

Safety critical systems shouldn’t have single points of failure

- This is the normal mode of design in automotive industry

Toyota tried to mitigate such risks, including in software

- But missed some dangerous single points of failure
  - Failed to prevent or contain faults …
- **There are single points of failure in the ETCS**
  - Some demonstrated in 2005 and 2008 Camry L4 vehicles
  - Unpredictable range of vehicle misbehaviors via task death
  - Other memory corruptions can be expected

INDIVIDUAL TASK DEATH OUTCOMES
(Watchdog should have detected them all!)

Task Death	Response (Fail-Safe)
1 ms task	ECM Reset (watchdog)
wheel speed	Not Detected
crank speed	Not Detected
engine speed	Not Detected
sigma task	stall (comm. Check)
motor control	if accel change stall (sys guards)
spark on cyl. 1	Not Detected
spark off cyl. 1	Not Detected
spark on cyl. 2	Not Detected
spark off cyl. 2	Not Detected
spark on cyl. 3	Not Detected
spark off cyl. 3	Not Detected
spark on cyl. 4	Not Detected
spark off cyl. 4	Not Detected
fuel injection	stall (mechanical)
10° task	Not Detected
30° med	stall (mechanical)
Task X	if brake change cut-stall (echo)
duty solenoid	Not Detected
rcv a task	if accel change cut (echo)
rcv b task	if brake change cut (echo)
8 ms task	stall (immobilizer)
30° low	Not Detected
idle task	Not Detected

Sources: Arora and Loudon Vehicle Testing; source code analysis. *Legend: “Not Detected” means in at least one vehicle test.*

THE TEST SPACE IS EFFECTIVELY INFINITE

There are >16 million combinations of task death

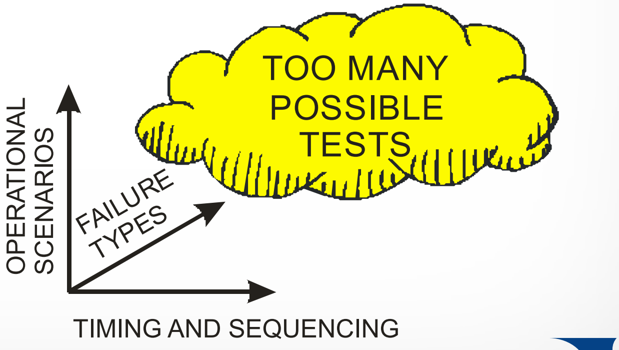
- Memory corruption can kill 1, 2, or all 24

Each task can die in thousands of different states

- Vehicle operational states (e.g., cruise on/off; accel 5% vs. 50%)

  And what happens next; driver reactions to misbehaviors; etc.

- Internal software states

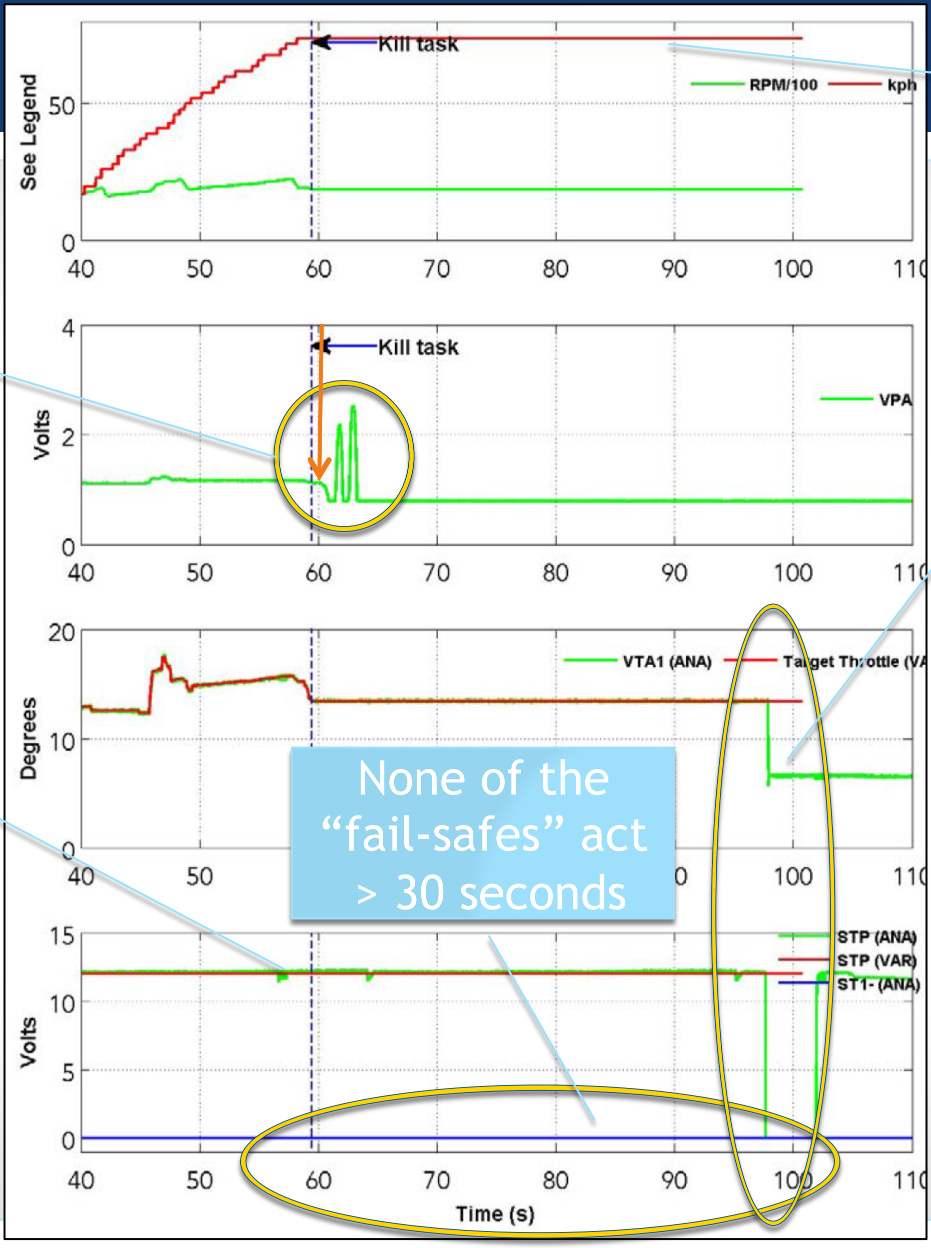


Test "samples" so far confirm

- Claimed fail-safes inadequate!

Barr Chapter Regarding
Task Death and UA

UA FOREVER IF BRAKE ON AT TASK DEATH



Vehicle speed is ~ 45 mph

Gas pedal does not affect speed any more!

Fail-safe acts only after driver removes foot (fully) from brake

Brake on (even lightly) at start of task death

None of the "fail-safes" act > 30 seconds

Source: Loudon St. John Report

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CASE-SPECIFIC OPINIONS

ETCS misbehavior is **more likely than other causes**

- Car should have stopped in less distance if throttle not open (*McCort*)
- Eyewitness testimony of alert driver using brakes (*Mrs. Schwarz*)
- No evidence of pedal entrapment by a floor mat (*photos*)
- No mechanical problems found at any vehicle inspection (*experts*)

Cannot identify with 100% certainty the specific software defects

- Toyota's software design "deletes" evidence of software problems

  Restart car and engine is fine (Toyota should have logged errors)

More likely than not undetected Task X death

- Many brake pumpers don't fully release the brake pedal (Cooper)
- "Car sped up when brakes were pumped" makes sense

OTHER SIMILAR INCIDENT CRITERIA

Vehicles with substantially similar ETCS software

- e.g., 2005-2009 Camry

Incidents with no apparent mechanical cause

- Lack of support for floor mats trapping accelerator pedal
- No indication of any mechanical issue before or after

Driver and witness statements describe UA

- And no evidence contradicting correct use of pedals

OSI Sources: NHTSA complaint database, Toyota FTRs, claims

TOYOTA'S EXPERT'S EVOLVING STATEMENTS

ETCS contains "layers of protection" (*Jul 2012*)

- True, but misses the key point: there are gaps thru those layers

Brake echo is a "designed fail-safe" (*Sep 2012-Aug 2013*)

- No, IF it were "by design" the fail-safe
  - would NOT require the driver to act <u>before</u> the fail-safe!
  - would NEVER require removal of foot from brake pedal
    - counter-intuitive (in an emergency!) and likely to increase (!) risk of harm
  - would NOT stall the engine (*given ECM reset is correct & safer*)

"It depends on how much fuel" (*Sep 2013*)

TOYOTA’S EXPERT HAS NOT REBUTTED

My *Operating System* opinions/chapter
My *Software Bugs* opinions/chapter
My *Memory Protections* opinions/chapter
My *Software Architecture* opinions/chapter
My *Watchdog Supervisor* opinions/chapter
My *Fail-Safe Modes* opinions/chapter
My *MISRA-C Violation* opinions/chapter
My *Coding Standard* opinions/chapter
My *Code Complexity* opinions/chapter
My *Stack Analysis* opinions/chapter

Most of Dr. Koopman’s opinions/report