JRC’s thermal runaway propagation test campaign at pack and vehicle level

25th GTR EVS meeting
29 November - 01 December 2022

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JRC experimental TP activity

Cell & material

Comparison of initiation techniques

- Trigger energy/ energy release

+ ARC, DSC

Short stack

Analyse influential factors on the outcome

- Temperature, SOC…
- Cell orientation
- Cell separation

Module

Evaluate repeatability, reproducibility

- Check proposed test descriptions (also with testing bodies)
- Round robin tests
- Define pass/fail criteria

Pack, Vehicle

Verification and finalization of method

- *Round robin tests*
- Practical aspects
- Define robust evaluation methods (e.g. gas analysis)

Narrow down init. methods

Refine test description

Select equivalent test(s)

DUTs - Car A and packs

- Factory-new contemporary commercially-available electric vehicle and 2 packs
- Li-ion battery
- 52 kWh, 12 modules, 192 cells
- Pouch cells
- NMC 622 / graphite chemistry
- MY 2021
- Tested under conditions closely matching “(c) temporary parking” mode

EVS24-E1TP-0300 [EC]JRC's thermal runaway propagation test campaign at .pdf

DUTs - Car B

- Factory-new contemporary commercially-available electric vehicle
- Li-ion battery pack
- 37.9 kWh, 8 modules, 96 cells
- Large prismatic cells with Al casing
- NMC / graphite chemistry
- MY 2021
- Tested in “(c) temporary parking” mode

Experimental set-up

Ambient conditions:

DUTs type A

T: 20-27°C
Wind: mostly wind-still conditions
wind breakers

T: 18-20°C
Wind: average speed 11 km/hr
wind breakers

Pool to contain water after fire extinguishing

Fire fighters in stand-by

Applus IDIADA

Test performed at Applus IDIADA in Tarragona, Spain

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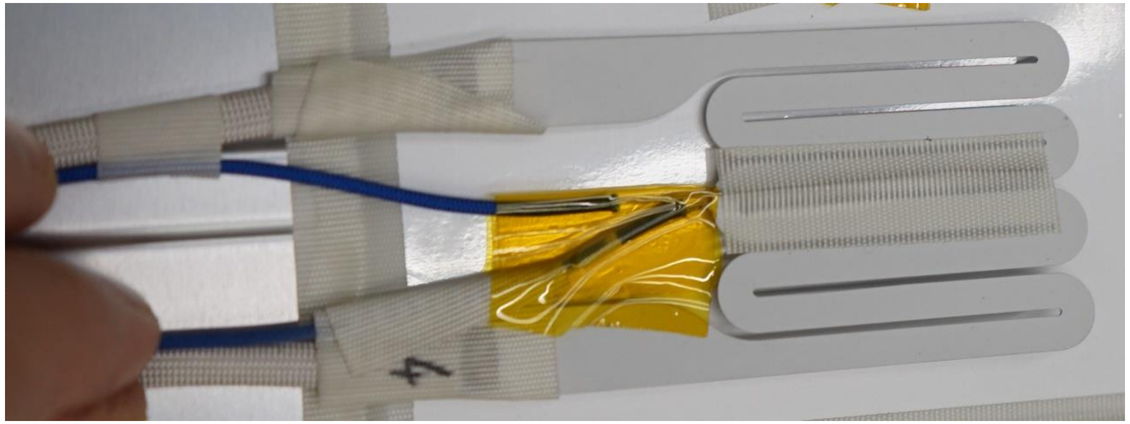
Triggering method



Canada
NRC·CNRC
Transport Canada / Transports Canada

"Apparatus and Method for initiating Thermal Runaway in a Battery" with application date of January 18, 2018. PCT/CA2018/050055

- Rapid external heating
- V5 elements developed by NRC Canada
- Active heating area: 39 mm x 55 mm ($21.5\ cm^2$)
- Thickness of the element: 0.7 mm
- Thickness of connections: 0.7 mm

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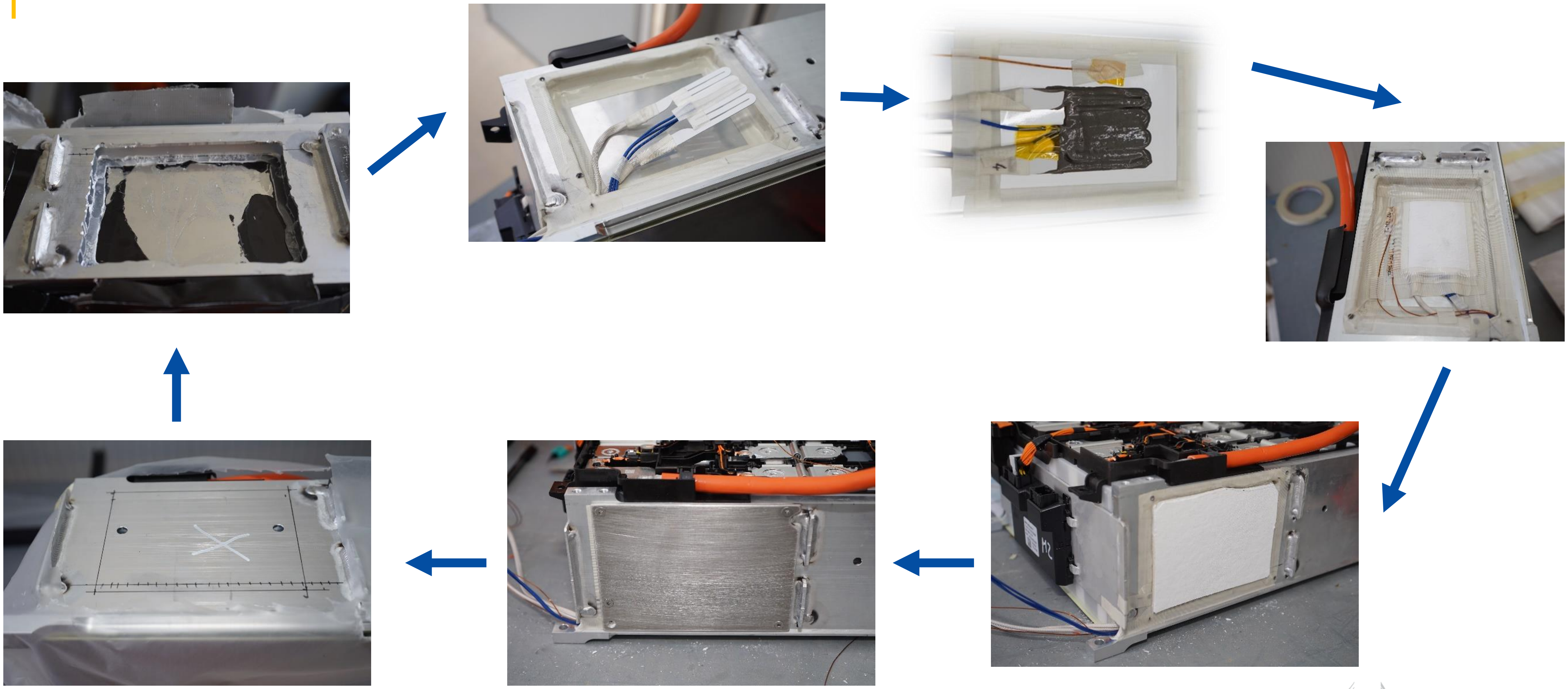
Instrumentation – TRIM installation



Instrumentation – thermocouples in the pack

front (left side of the layout) – rear (right side of the layout)

M5 – 6 TCs						M6 – 9 TCs						M7 – 10 TCs						M8 – 6 TCs					
50 *	51	54 *	55	58	59 *	62 *	63	66 *	67	70 *	71 *	74 *	75 *	78	79 *	82	83 *	86 *	87	90	91 *	94	95 *
49 *	52	53 *	56	57	60 *	61 *	64	65 *	68	69 *	72 *	73 *	76 *	77	80 *	81	84 *	85 *	88	89	92 *	93	96 *
48 *	45	44 *	41	40	37 *	36 *	33	32 *	29	28 **	25 **	24 7*	21 **	20 **	17 *	16 *	13 *	12 *	9	8	5 *	4	1 *
47 *	46	43 *	42	39	38 *	35 *	34	31 *	30	27 *	26 **	23 **	22 **	19 *	18 *	15 *	14 *	11 *	10	7	6 *	3	2 *
M4 – 6 TCs						M3 – 11 TCs						M2 – 22 TCs						M1 – 6 TCs					

Initiating cell (red cell: 24) M1 – module number 6 TCs – number of thermocouples in the module

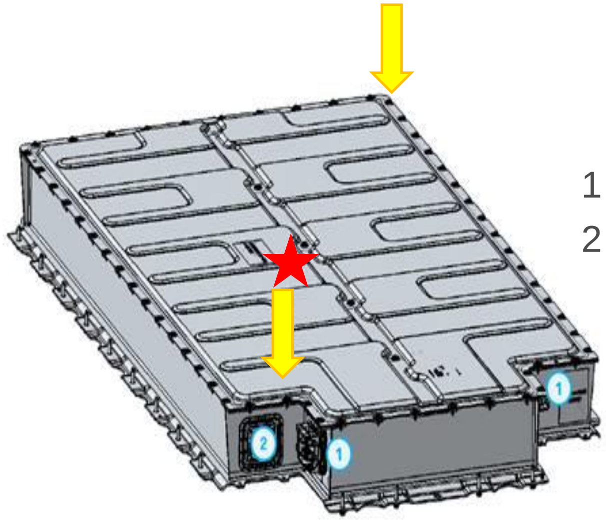
Number of * indicate number of TCs for a given cell

Instrumentation – other sensors

- Initiating module cell voltages
- Module temperatures and voltages
- Temperatures on the exterior of the packs
- Temperatures inside the passenger cabin of a vehicle
- Pressure sensors in the packs
- Video and IR footage
- Smoke and hazardous gas detectors in the passenger cabin
- Gas analysis:
    - Online FTIR
    - Offline (canisters + GC)
    - Washing bottles (HF)
    - Open path FTIR

Instrumentation – pressure sensors

- Two “off-the-shelf” commercially available pressure sensors were installed as indicated by the yellow arrows.



1 Electric plugs
2 Pack’s vent

Position of pressure sensors

Position of initiation cell

Time sequence of the events – Car B

Start of data logging	13:55:49
Start TRIM	14:05:50
First warning on a dashboard	14:06:57
Stop TRIM	14:07:09
Smoke external to the vehicle	14:07:12
CO alarm in the cabin (25 ppm)	14:14:55
Smoke in the cabin	14:27:07
Visible flames inside the cabin	14:37:43
Visible flames external to the vehicle	14:37:46
Time to smoke external to the vehicle	2 min 22 s
Time to CO alarm (25 ppm) in the cabin	9 min 05 s
Time to smoke in the cabin	21 min 17 s
Time to flames in the cabin	31 min 53 s

Thermal runaway evaluation

Energy added

Thermal runaway was successfully initiated in all cases using TRIM heater V5

DUT	Energy added, Wh	Energy added, % of cell's electric energy	Comment
Pack #1 A	**n.a.**	**n.a.**	
Pack #2 A	**3.9**	**1.3**	*
Car A	**4.0**	**1.3**	*
Car B	**16.2**	**3.2**	**

* Good agreement with previous JRC experiments at cell, short stack and module levels (see e.g. EVS20-E1TP-0500 [EC]Progress on thermal propagation testing.pdf)

** Good agreement with experiment of NRC Canada at module level (2.9%)

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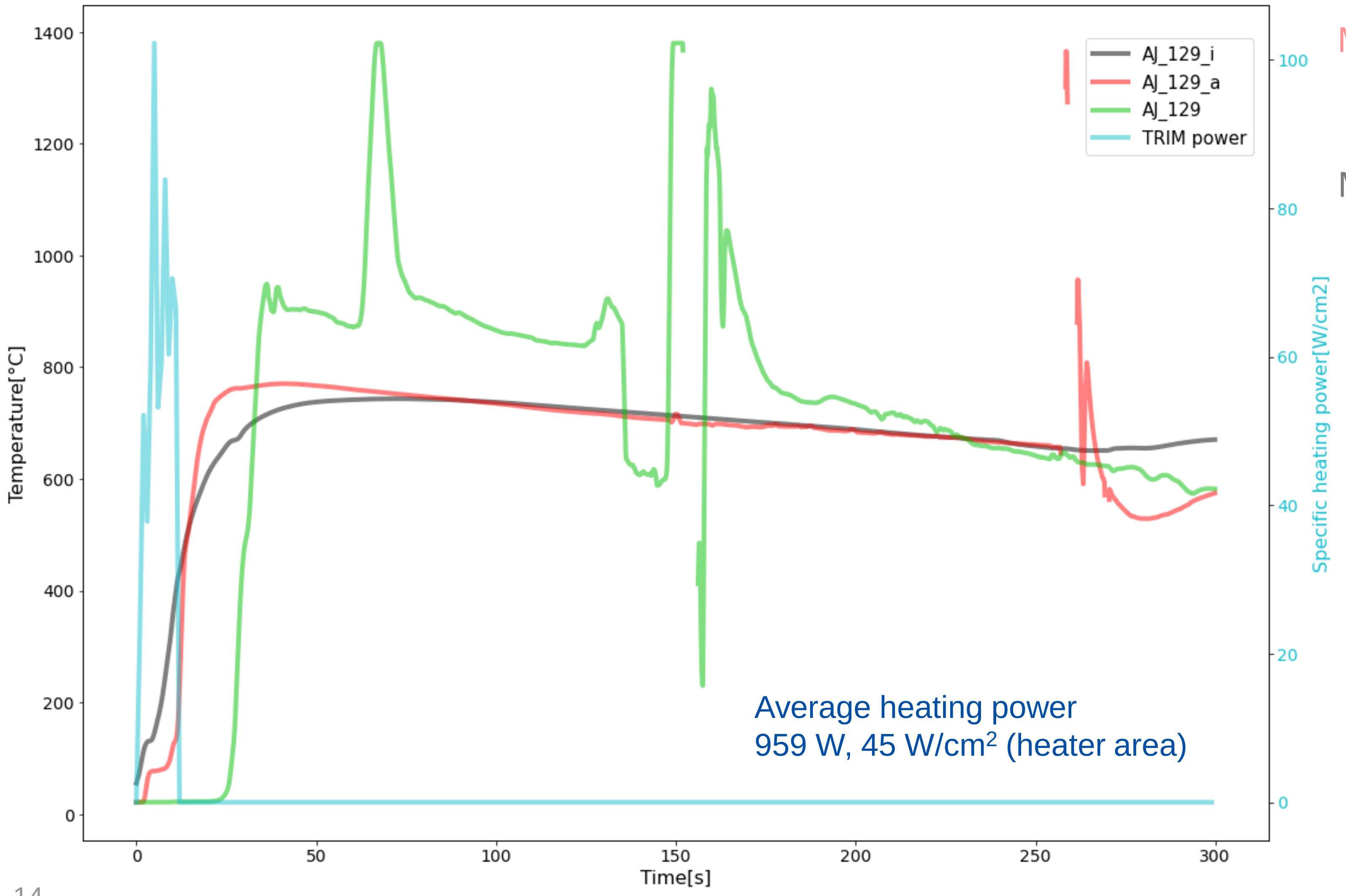
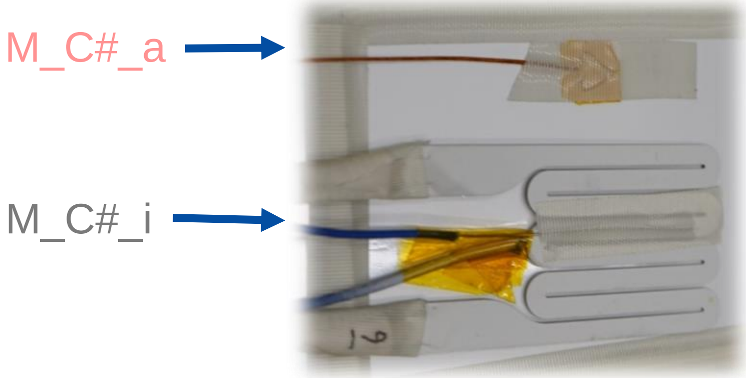
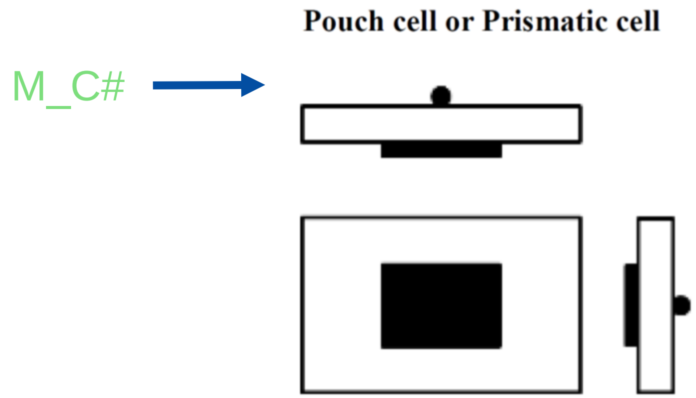
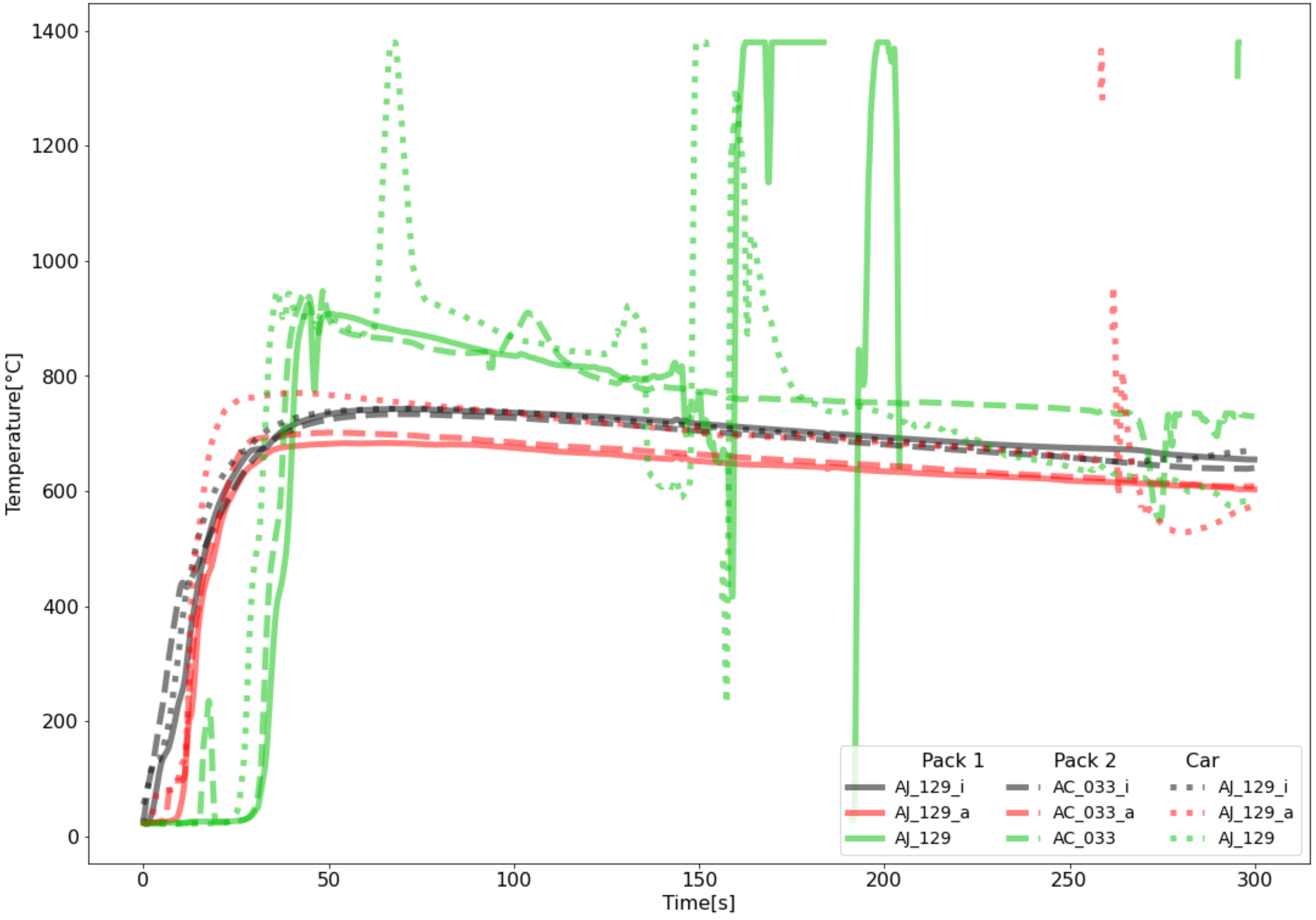
Temperature of the initiation cell – Car A

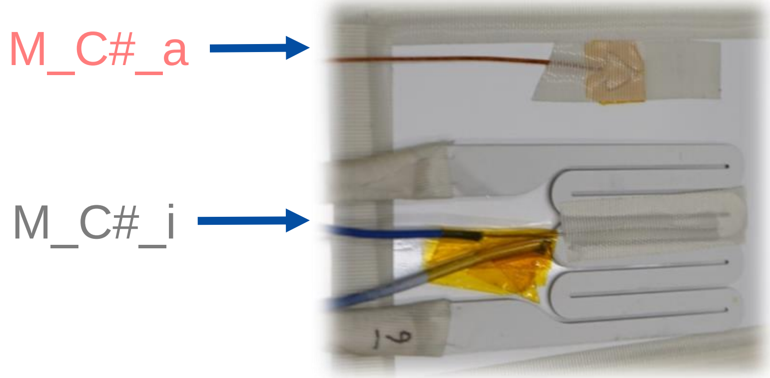




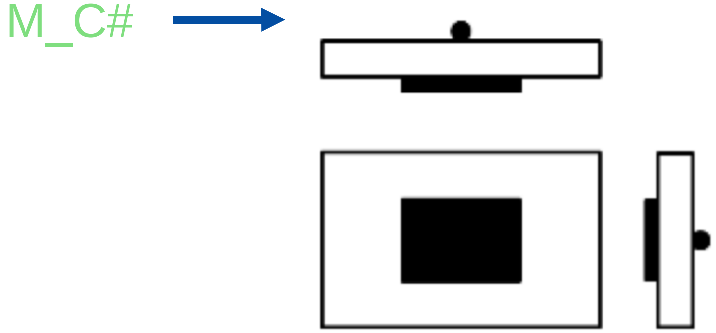


Temperature of the initiation cell – DUTs type A





Pouch cell or Prismatic cell



Thermal runaway initiation using TRIM heater V5 is reproducible for tested DUTs

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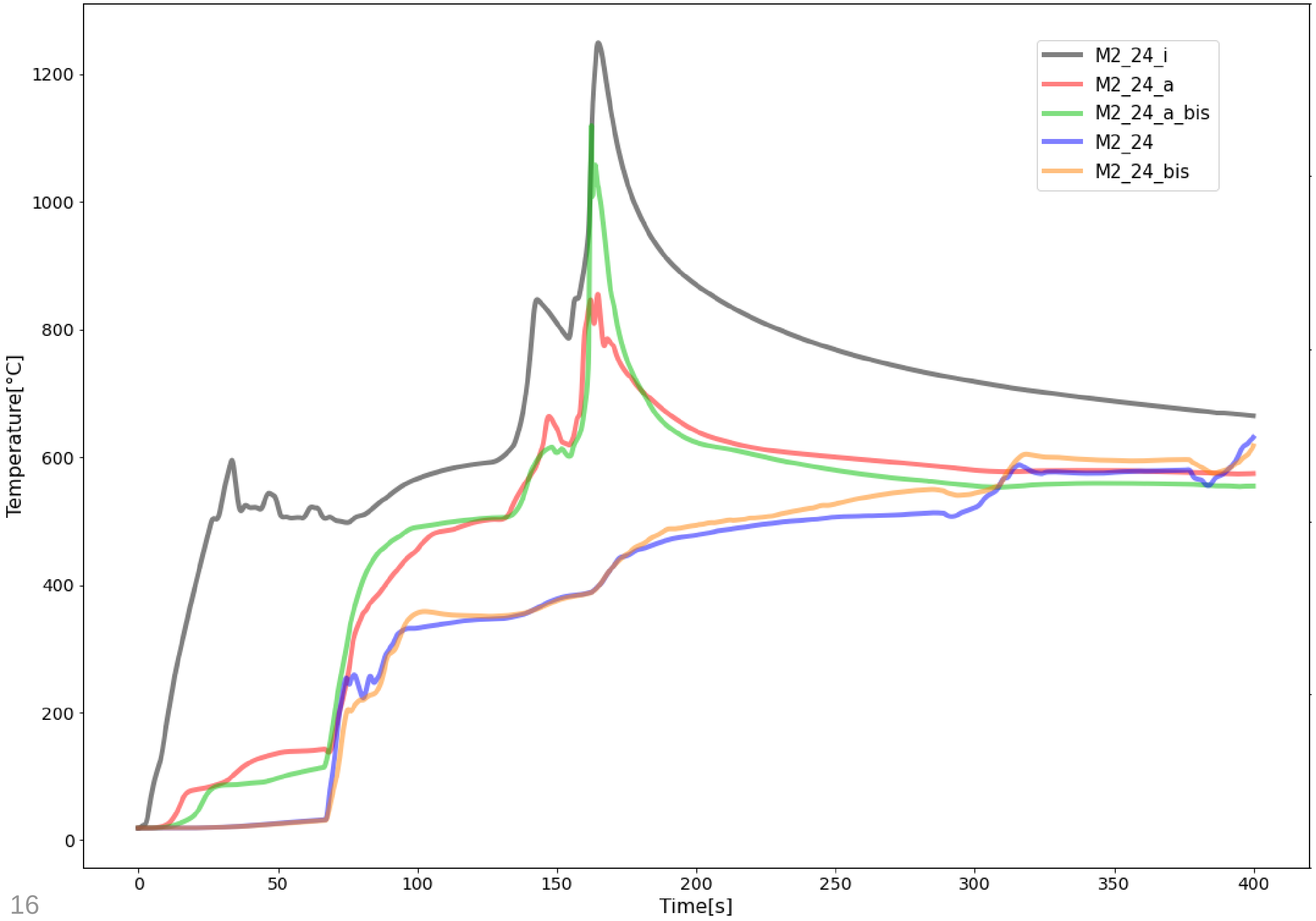
Temperature of the initiation cell – Car B



M_C#_a

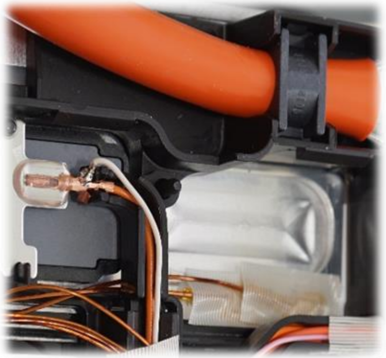
M_C#_a_bis

M_C#_i

M_C#

M_C#_bis

(next to the vent)



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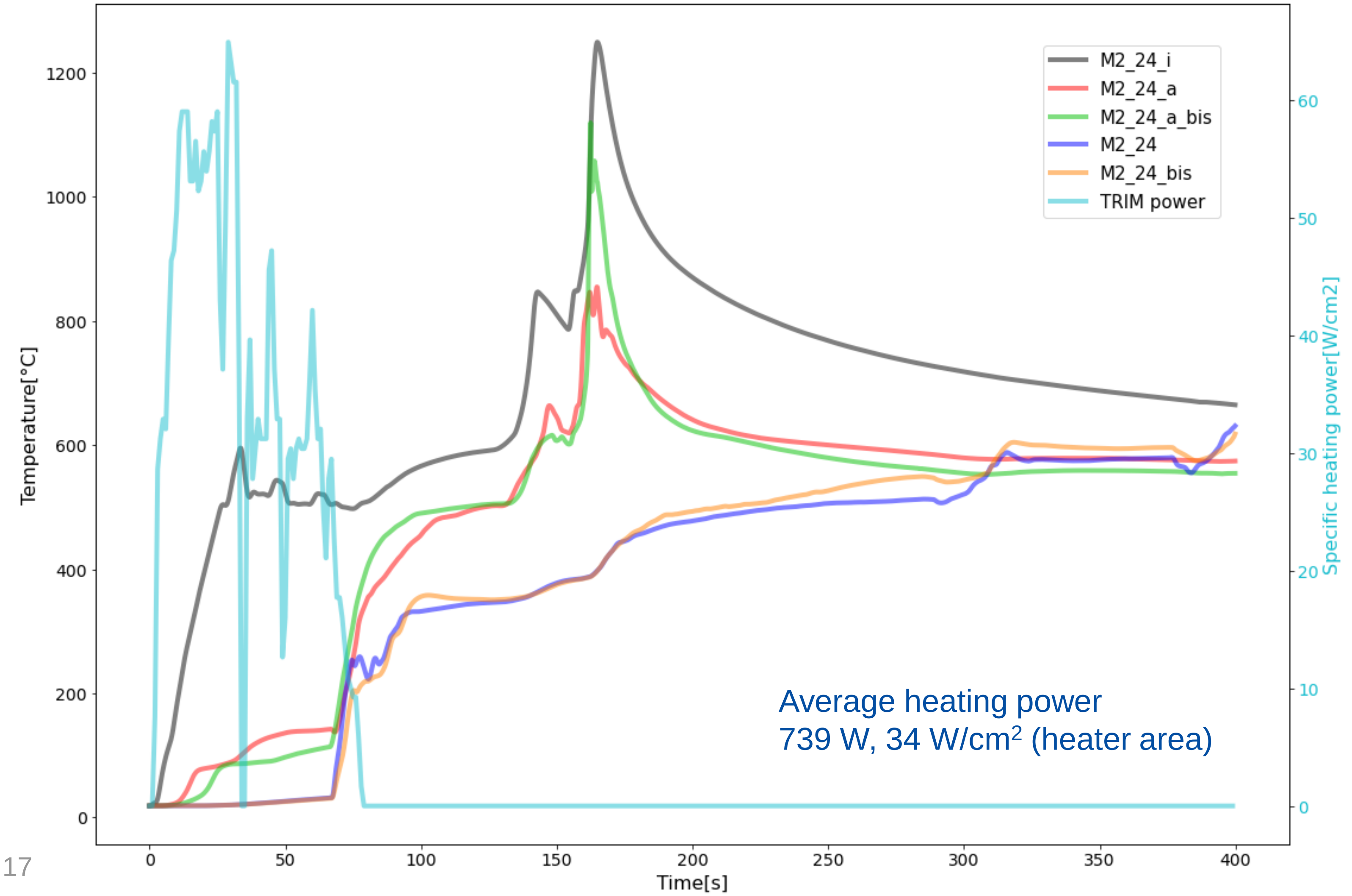
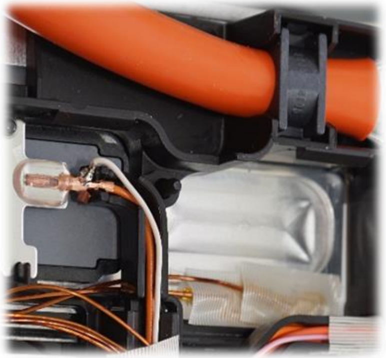
Temperature of the initiation cell – Car B



M_C#_a
M_C#_a_bis
M_C#_i

M_C#
M_C#_bis
(next to the vent)



Thermal runaway (TR) criteria

Different sets of TR criteria were tested:

1) The measured cell temperature (T_{cell}) exceeds the maximum operating temperature defined by the manufacturer (T_{max}) and the measured cell temperature change rate (dT_{cell}/dt) exceeding 1°C/s, i.e. $T_{cell} > T_{max}$ and $dT_{cell}/dt > 1$°C/s; (**GTR phase 1**)

2) The measured voltage of the initiation cell (V) drops and the measured cell temperature change rate (dT_{cell}/dt) exceeding 1 K/s, i.e. $V < V_{ini}$ and $dT_{cell}/dt > 1$°C/s; (**GTR phase 1**)

3) $T_{cell} > T_{max}$ and $dT_{cell}/dt > 15$°C/s, both parameters for at least 0.5 s; (**ISO 6469-1/DAM1**)

4) $V < 0.75 \times V_{ini}$ and $dT_{cell}/dt > 1$°C/s at least for 3 s (**GB 38031-2020**)

5) $T_{cell} > T_{max}$ and $dT_{cell}/dt > 1$°C/s at least for 3 s (**GB 38031-2020**)

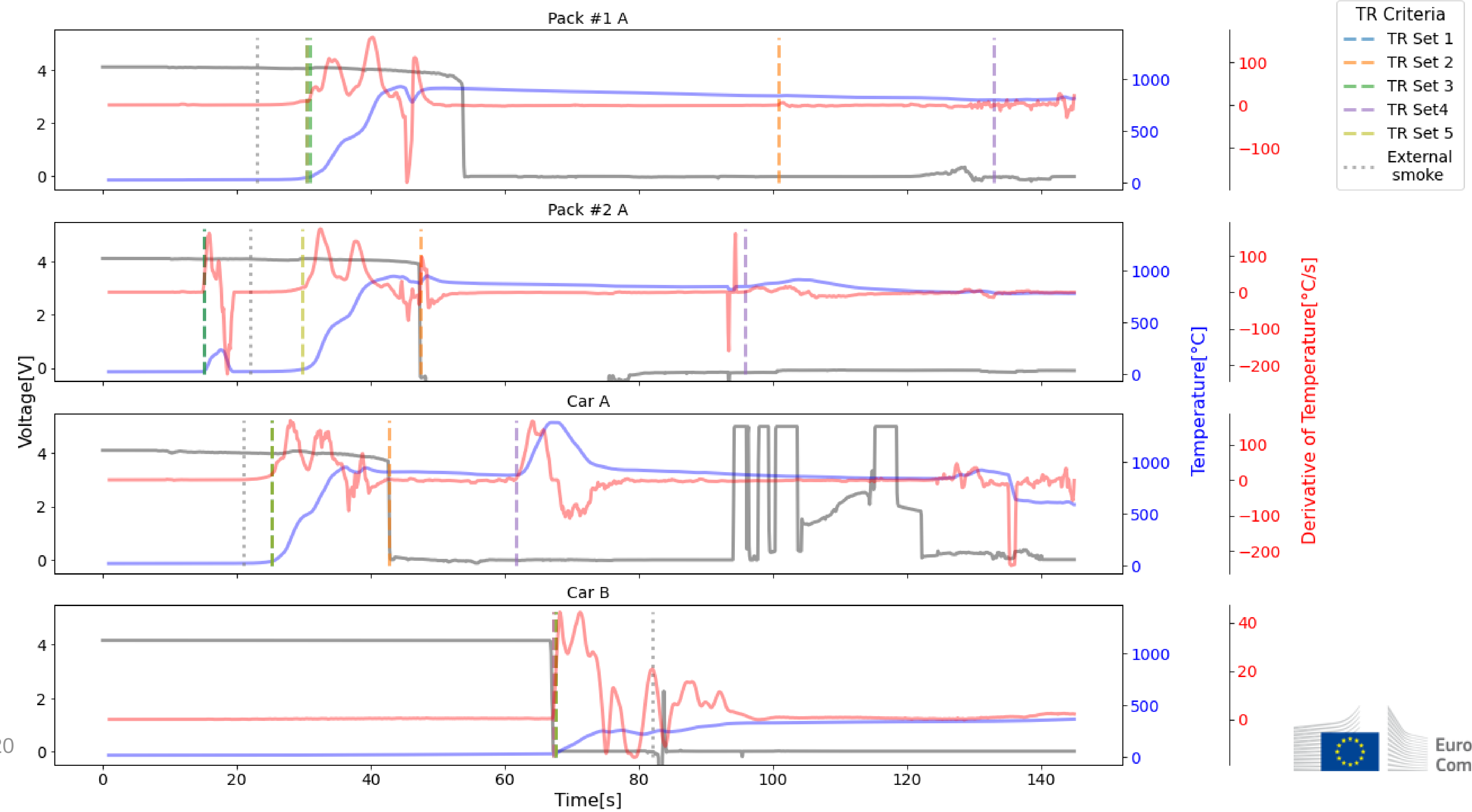
Thermal runaway (TR) criteria

Data acquisition and processing:

1) Sampling frequency for temperature, voltage and pressure signals was 10 Hz.

2) Moving average filter with 1 s window was applied for data processing, similar to our previous study (see e.g. EVS22-E1TP-0200 [EC]Thermal runaway criteria.pdf)

Thermal runaway criteria



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Thermal runaway criteria – sensitivity analysis

Voltage

The times for different voltage drop levels (to 75%, to 50% or to 25% of the initial value) were found to be identical for all DUTs, with the exception of Car A, that goes from 42.7s for a voltage drop to 75% of the initial value to 42.8s for the two other ones (to 50% or to 25% of the initial value);

Therefore, criteria set $V<V_{ini} + dT_{cell}/dt > 1°C/s$ is considered equivalent to $V< 0.75 \times V_{ini} + dT_{cell}/dt >1°C/s$ in this study.

Thermal runaway criteria – sensitivity analysis

Time period

For the minimum time period (variable) analysis:
T_{cell} > 50°C and dT_{cell}/dt > 1°C/s are constant;

dT_{cell}/dt

For the dT_{cell}/dt (variable) analysis:
T_{cell} > 50°C and minimum time > 3s are constant.

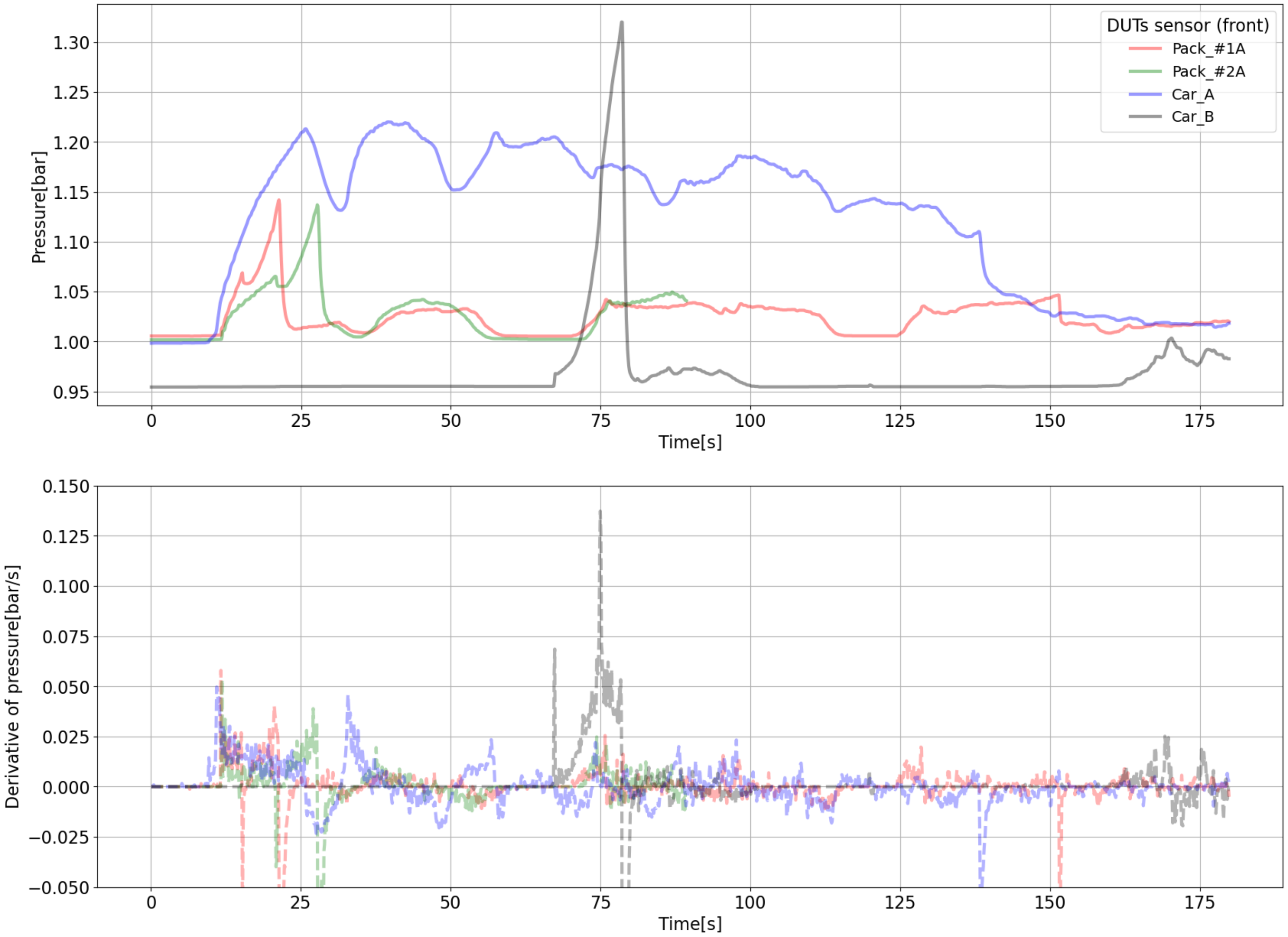
Min time interval [s]	Time of TR criteria flagged [s]			
	Pack #1A	Pack #2A	Car A	Car B
0.5	30.5	15.2	25.2	67.6
1	30.5	15.2	25.2	67.6
1.5	30.5	15.2	25.2	67.6
2	30.5	15.2	25.2	67.6
2.5	30.5	15.2	25.2	67.6
3	30.5	29.7	25.2	67.6
3.5	30.5	29.7	25.2	67.6
4	30.5	29.7	25.2	67.6
4.5	30.5	29.7	25.2	67.6
5	30.5	29.7	25.2	67.6
5.5	30.5	29.7	25.2	67.6
6	30.5	29.7	25.2	67.6
6.5	30.5	29.7	25.2	67.6
7	30.5	29.7	25.2	67.6

dT/dt [°C/s]	Time of TR criteria flagged [s]			
	Pack #1A	Pack #2A	Car A	Car B
1	30.5	29.7	25.2	67.6
3	30.5	29.7	25.2	67.6
5	30.5	29.7	25.2	67.6
7	30.5	29.7	25.2	67.6
9	30.7	29.7	25.2	67.6
11	30.9	29.7	25.2	67.6
13	30.9	30.2	25.2	67.6
15	31	30.3	25.2	67.6
17	31	30.4	25.3	67.6
19	31.1	30.4	25.5	67.6

Thermal runaway criteria

	Time when a set of criteria was met, s			
TR criteria	**Pack #1 A**	**Pack #2 A**	**Car A**	**Car B**
$T_{cell} > T_{max}$ + dT_{cell}/dt > 1°C/s	**30.5**	**15.2**	**25.2**	**67.6**
V< 0.75 x V_{ini} + dT_{cell}/dt >1°C/s	**100.9**	**47.4**	**42.7**	**67.2**
$T_{cell} > T_{max}$ + dT_{cell}/dt > 15°C/s for at least 0.5 s	**31.0**	**15.2**	**25.2**	**67.6**
V< 0.75 x V_{ini} + dT_{cell}/dt > 1°C/s for 3 s	**132.9**	**95.8**	**61.6**	**67.2**
$T_{cell} > T_{max}$ + dT_{cell}/dt > 1°C/s for 3 s	**30.5**	**29.7**	**25.2**	**67.6**

Pressure in the pack



For DUTs type A, higher pressure is achieved in a pack installed in a car (likely better gas tightness)

Pressure signal is found to be independent of the location of the sensor in a pack

Pressure change rate can be up to ca. 0.13 bar/s, depending on the DUT

Thermal runaway criteria – additional criteria

A potential TR criteria set?

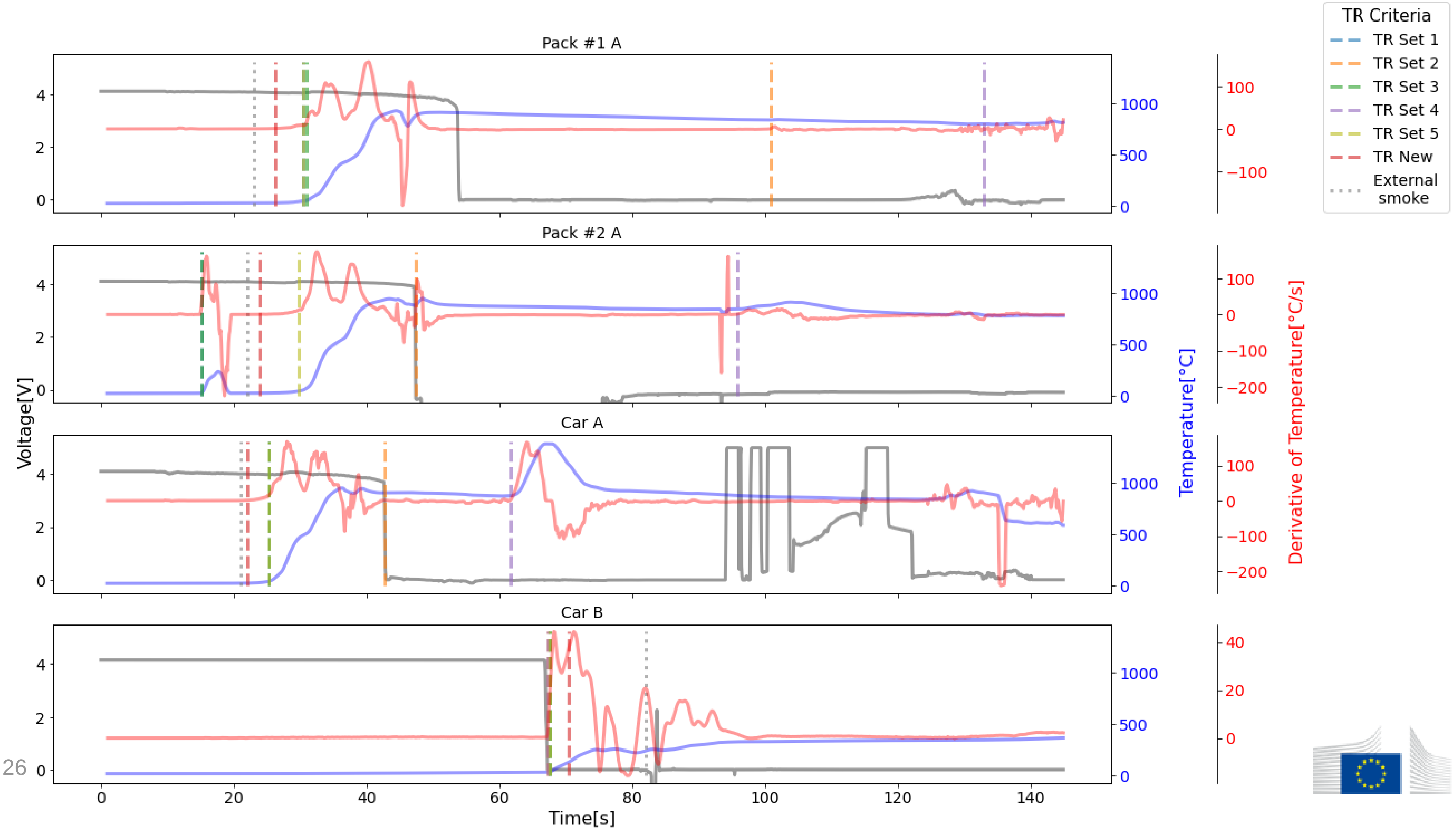
Rate of change of pressure in the pack combined with rate of change of measured cell temperature for at least 3 s:

$dP_{pack}/dt > 0.01$ bar/s + $dT_{cell}/dt > 1°C/s$ for at least 3 s

Value of 0.01 bar/s chosen after investigating typical rates of atmospheric pressure changes. These were found to normally be lower than 0.01 bar/s, which corresponds to a pressure change in a tornado [1].

1. Karstens, C. D., Samaras, T. M., Lee, B. D., Gallus, W. A., & Finley, C. A. (2010). Near-ground pressure and wind measurements in tornadoes. Monthly Weather Review, 138(7), 2570-2588.

Thermal runaway criteria – additional criteria



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Thermal runaway criteria

	Time when a set of criteria was met, s			
TR criteria	**Pack #1 A**	**Pack #2 A**	**Car A**	**Car B**
T_{cell}>T_{max} + dT_{cell}/dt > 1°C/s	**30.5**	**15.2**	**25.2**	**67.6**
V< 0.75 x V_{ini} + dT_{cell}/dt >1°C/s	**100.9**	**47.4**	**42.7**	**67.2**
T_{cell}>T_{max} + dT_{cell}/dt > 15°C/s for at least 0.5 s	**31.0**	**15.2**	**25.2**	**67.6**
V< 0.75 x V_{ini} + dT_{cell}/dt > 1°C/s for 3 s	**132.9**	**95.8**	**61.6**	**67.2**
T_{cell}>T_{max} + dT_{cell}/dt > 1°C/s for 3 s	**30.5**	**29.7**	**25.2**	**67.6**
dP_{pack}/dt > 0.01 bar/s + dT_{cell}/dt > 1°C/s for 3 s	**26.3**	**23.9**	**22.0**	**70.4**
dP_{pack}/dt > 0.01 bar/s for 3 s	**17.0**	**23.9**	**10.8**	**70.4**
TRIM heater power drops to 0 W	**n.a.**	**12.0**	**11.0**	**77.0**
Smoke external to DUT	**23.0**	**22.0**	**21.0**	**82.0**

Thermal runaway criteria

JRC research has shown that:

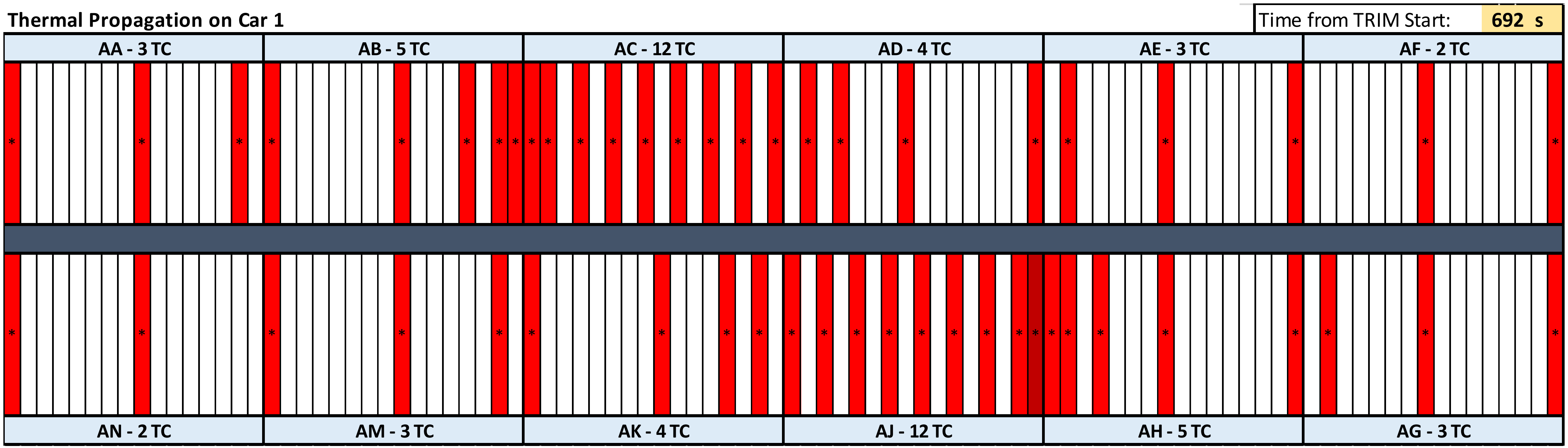
- TR criteria as currently defined in the GTR EVS text can detect TR, but in some cases lead to a delayed detection of TR.

- Voltage drop does not seem to be a reliable indicator of TR in systems with parallel-connected cells. For DUTs of type A in our study, the voltage drop value (to 75%, to 50% or to 25% of the initial value) was of no noticeable significance when determining the time of meeting the criteria. This is in agreement with the JRC's analysis of TR criteria at single cell level (see e.g. [EVS22-E1TP-0200 [EC]Thermal runaway criteria.pdf])

- In our experiments, criteria like heater power, pressure change rate in a pack and smoke external to the DUT could detect TR, in some cases even earlier than the criteria based on T_{cell}, dT_{cell}/dt and voltage drop.

Thermal runaway propagation

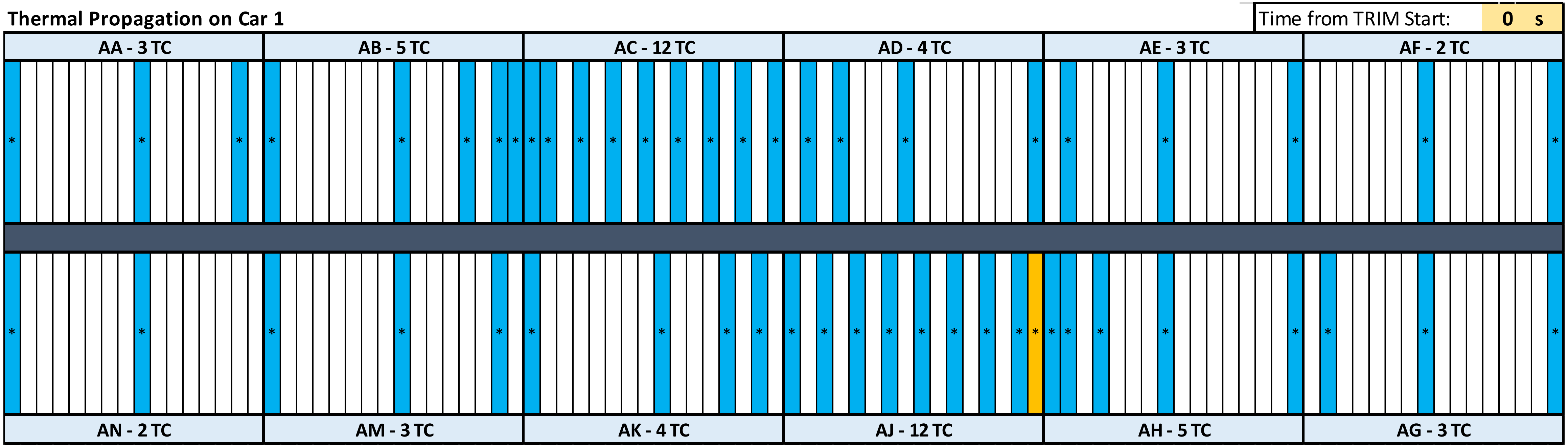
Thermal Propagation Car A



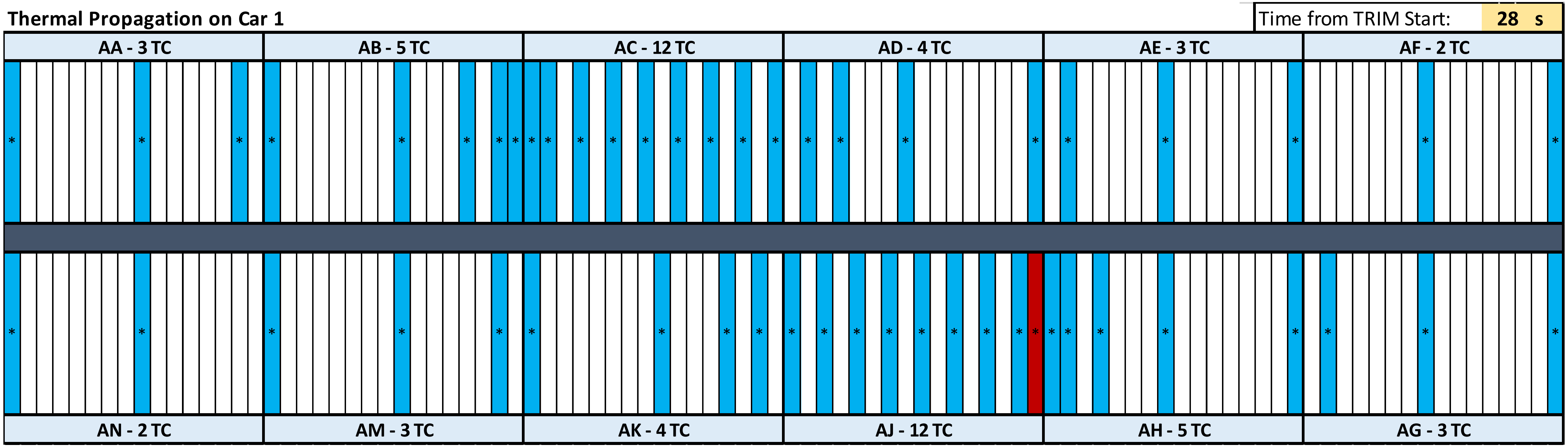
Hot vented gases play an important role in TP in this system leading to a “non-sequential” propagation, i.e. AJ-AM-AK modules

Cell turns red when its temperature exceeds 200°C

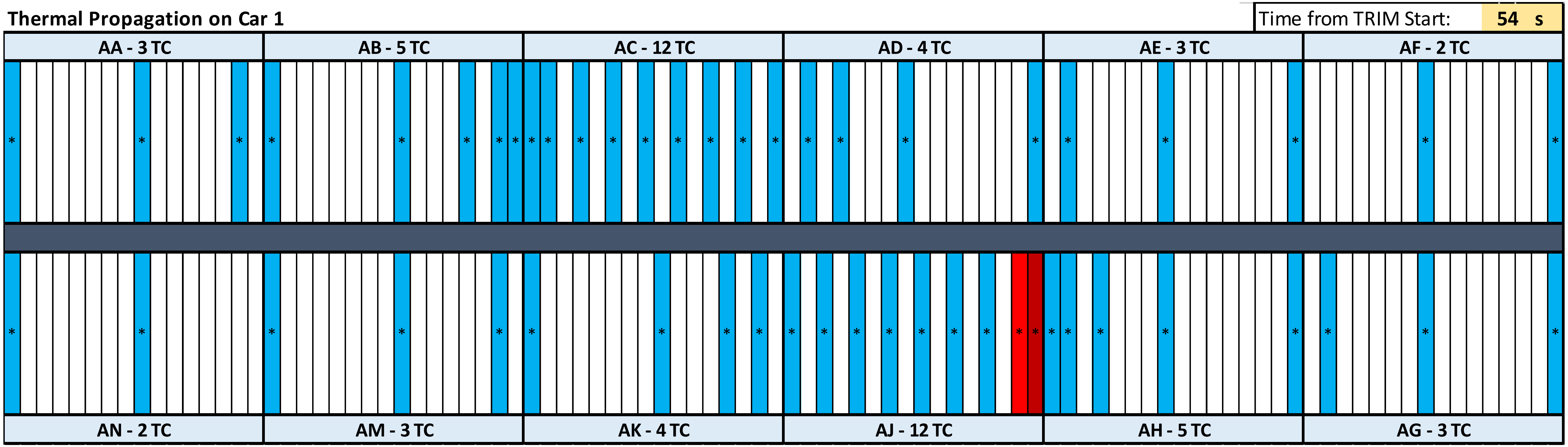
Thermal Propagation Car A



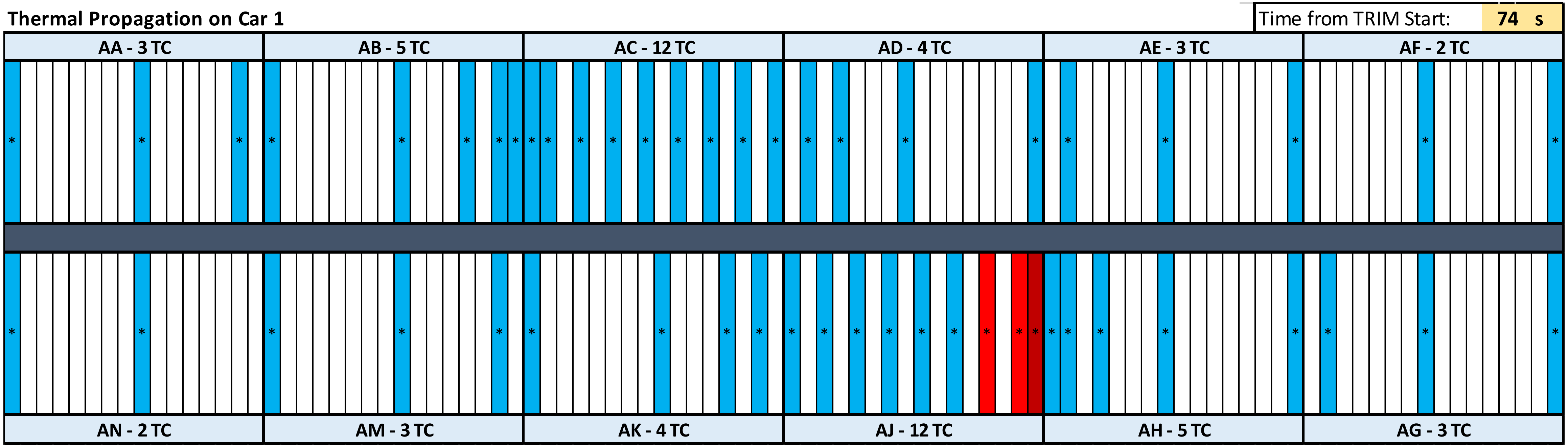
Thermal Propagation Car A



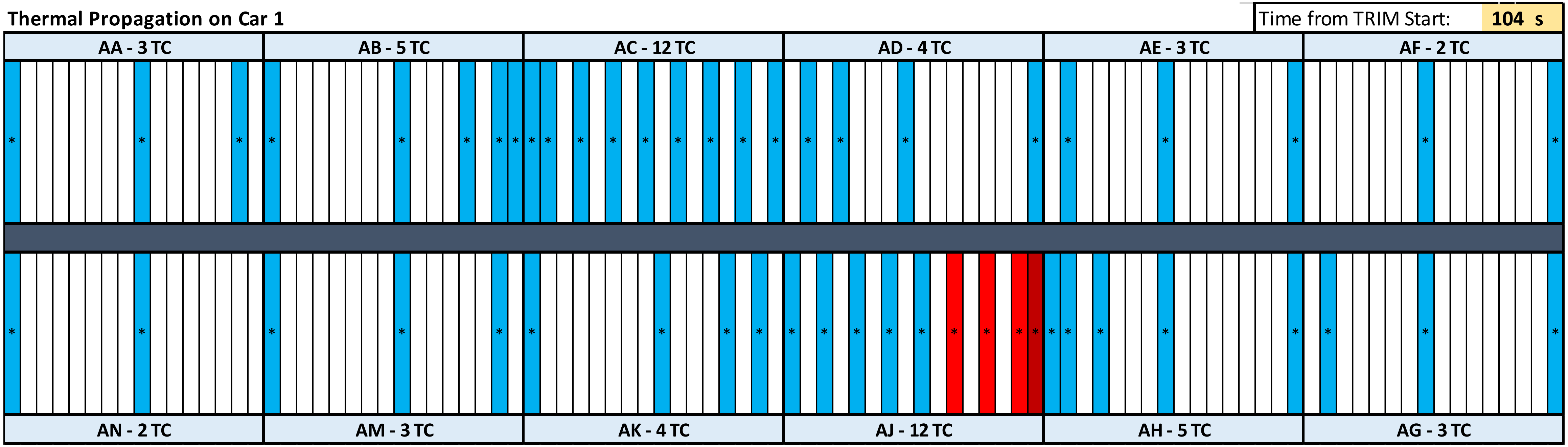
Thermal Propagation Car A



Thermal Propagation Car A



Thermal Propagation Car A



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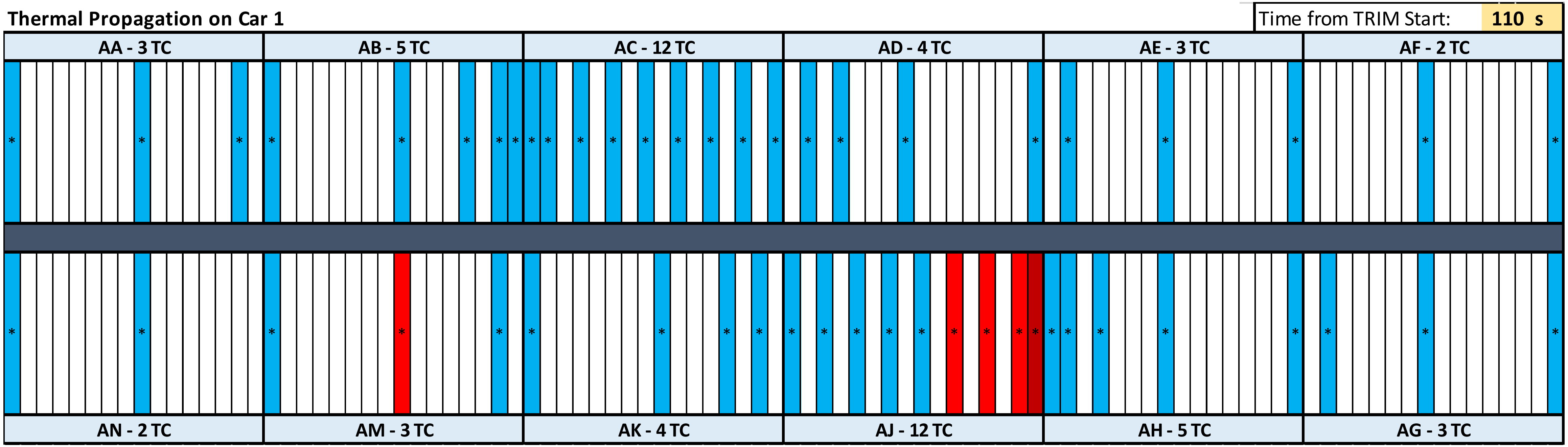

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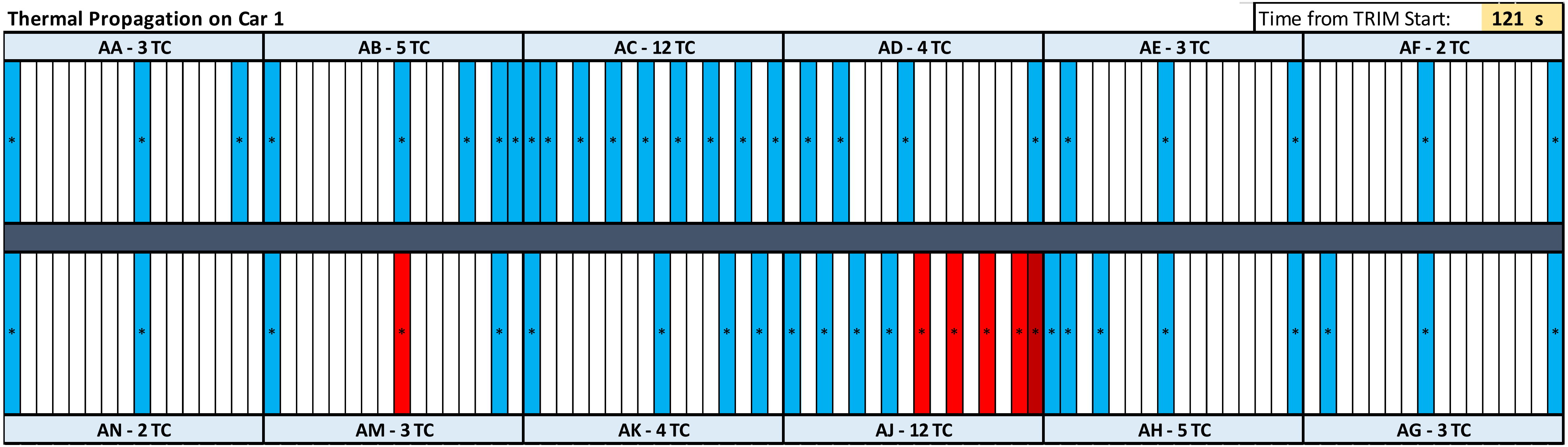
Thermal Propagation Car A



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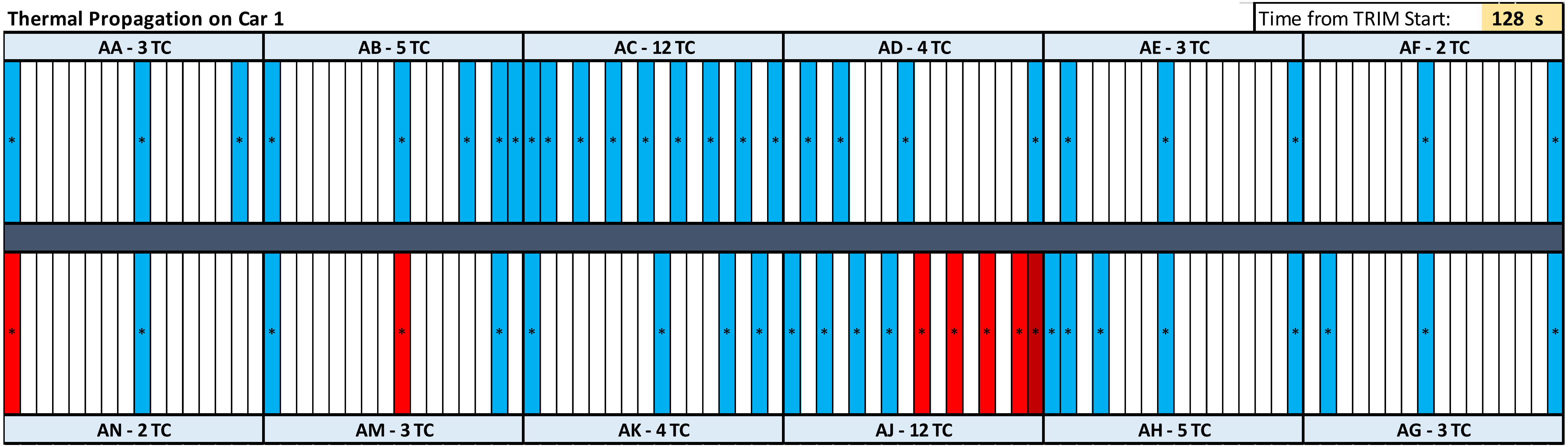

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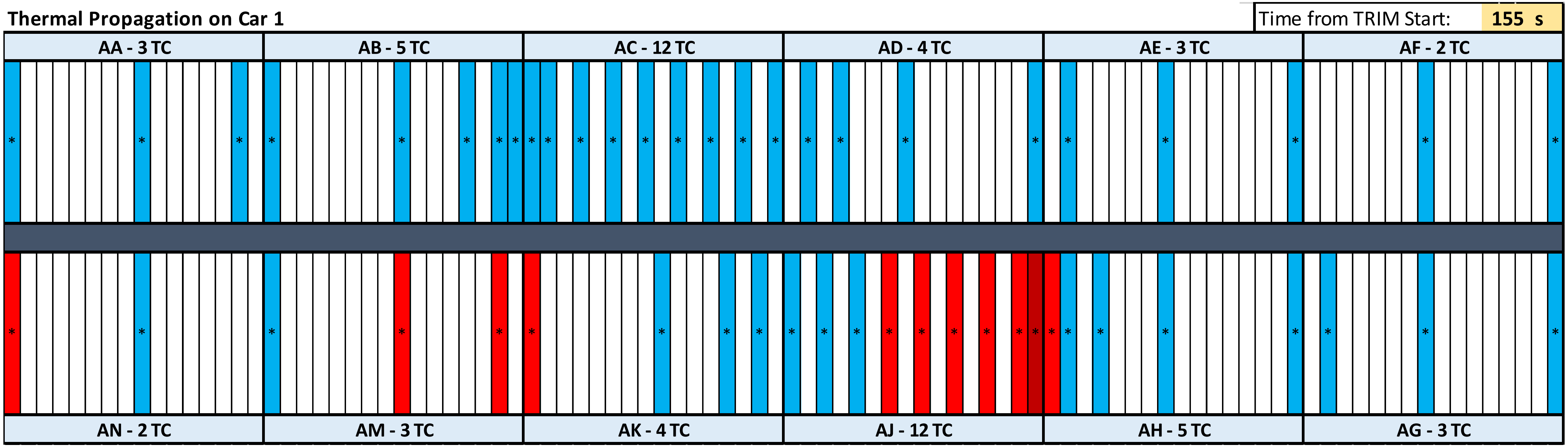

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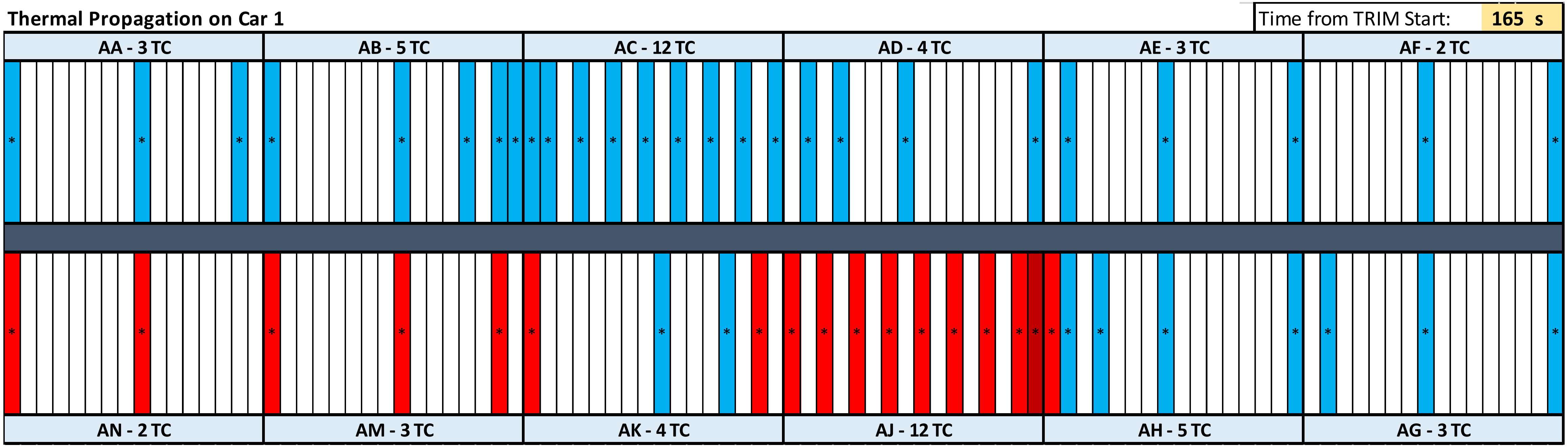

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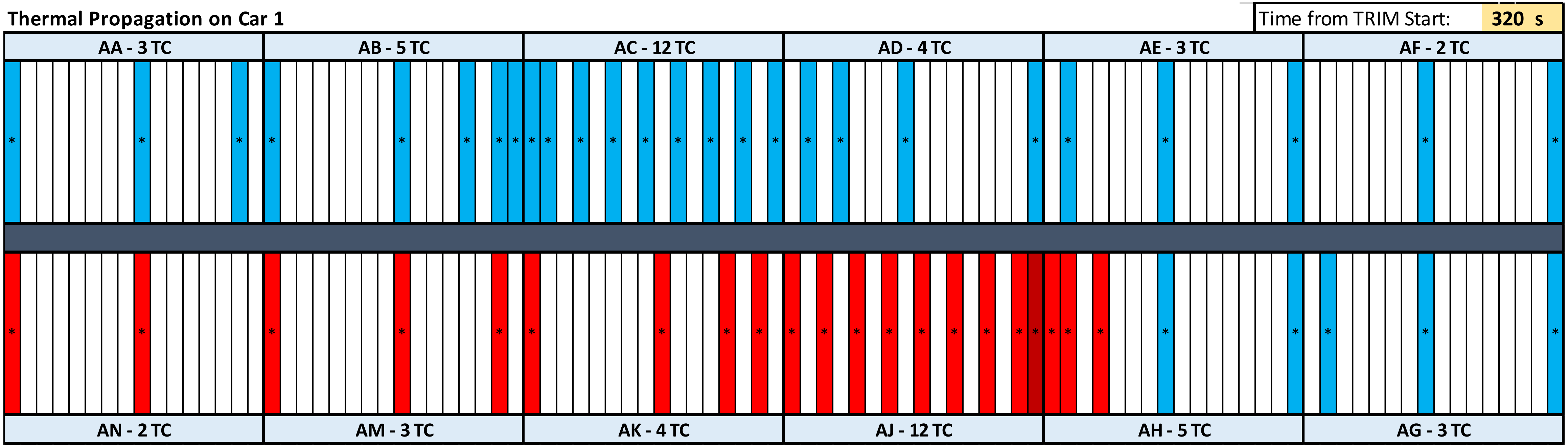

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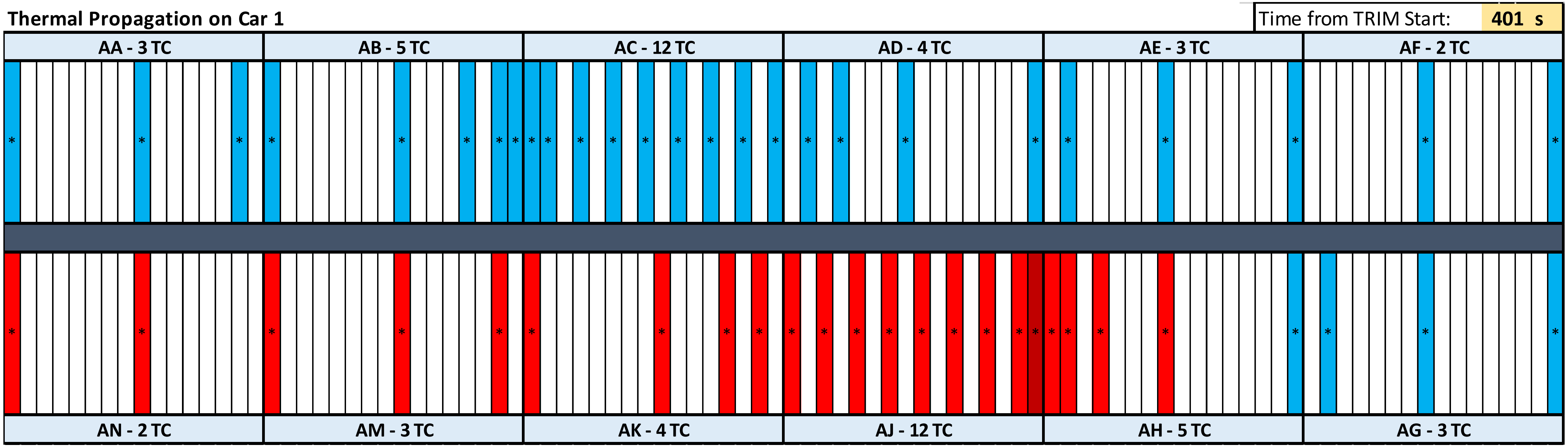

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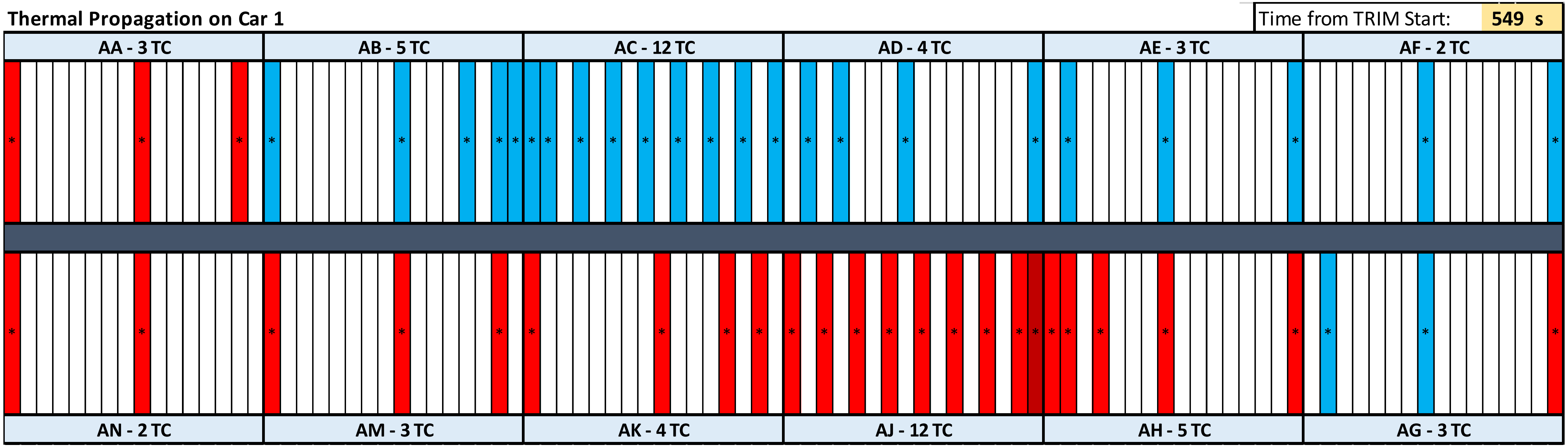

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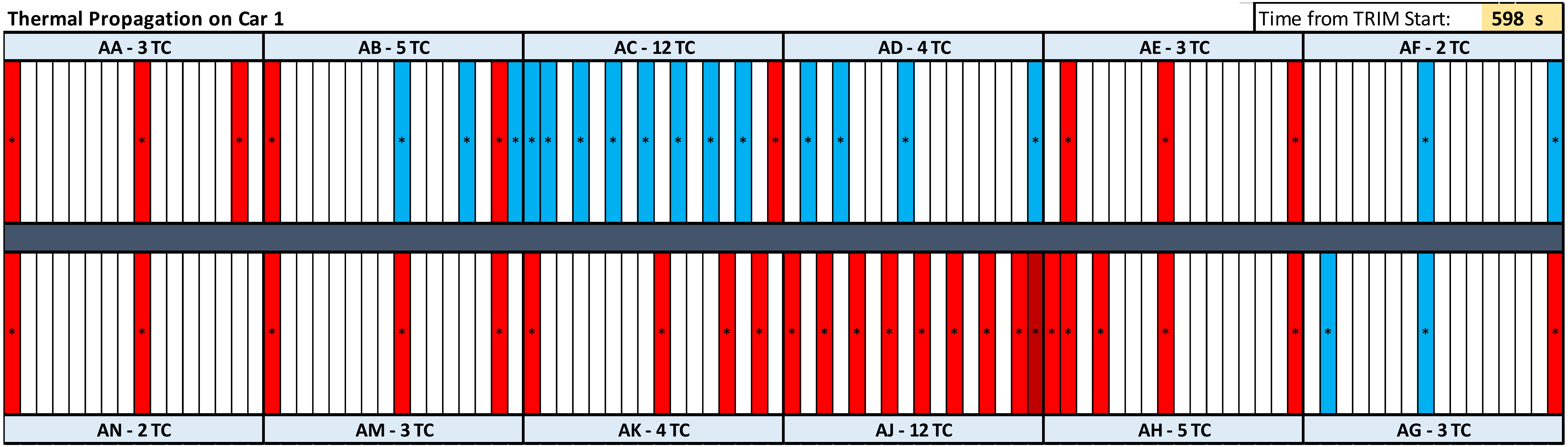
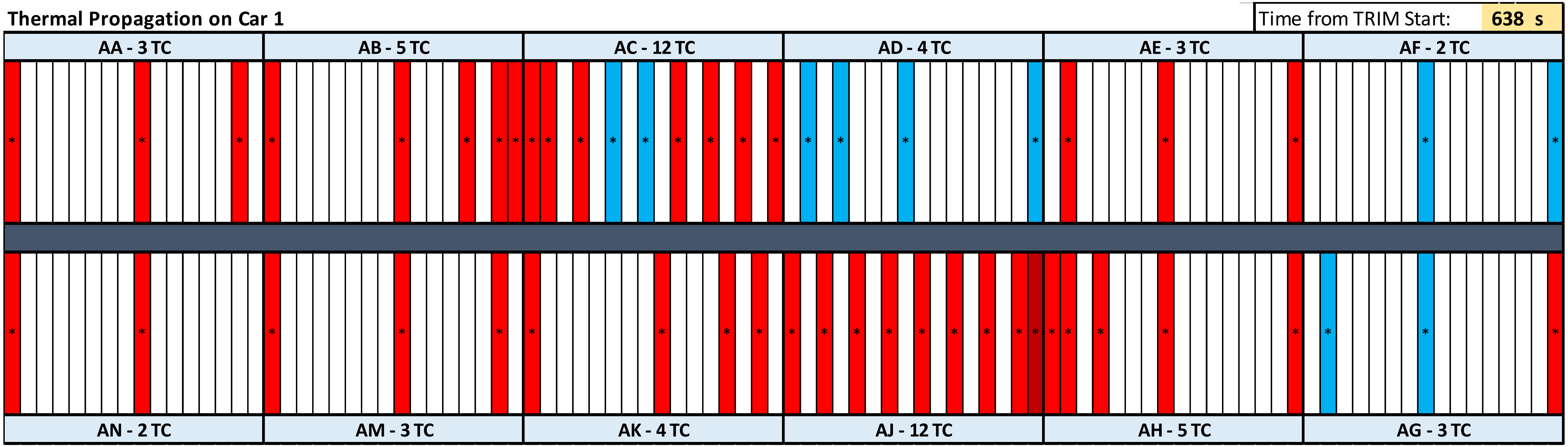
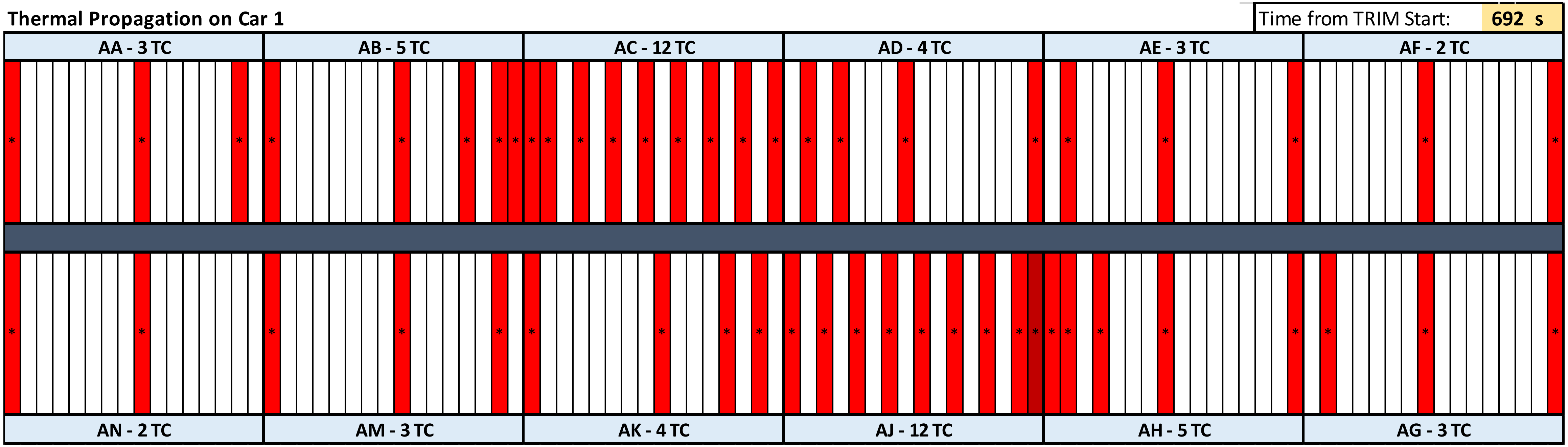


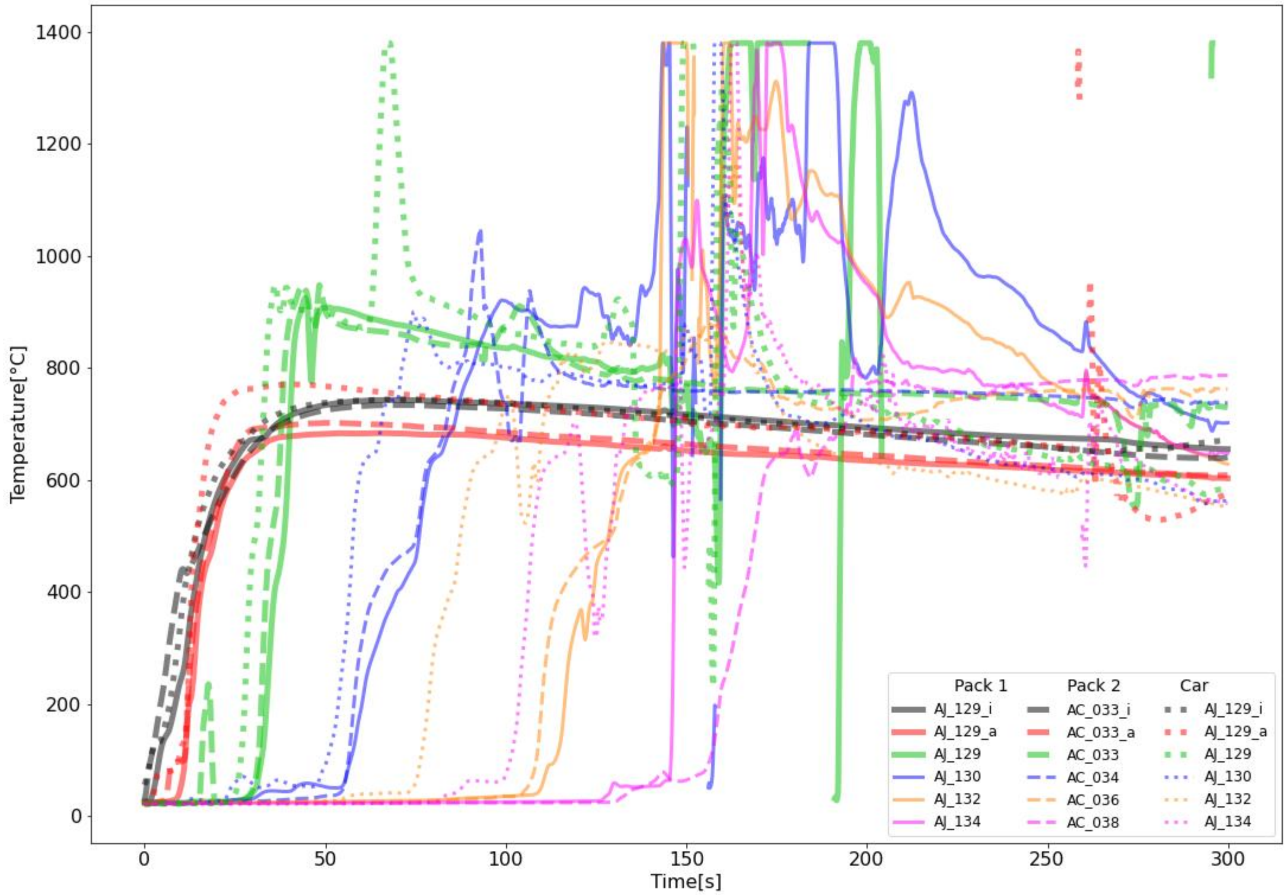
Thermal Propagation Car A



Thermal Propagation Car A

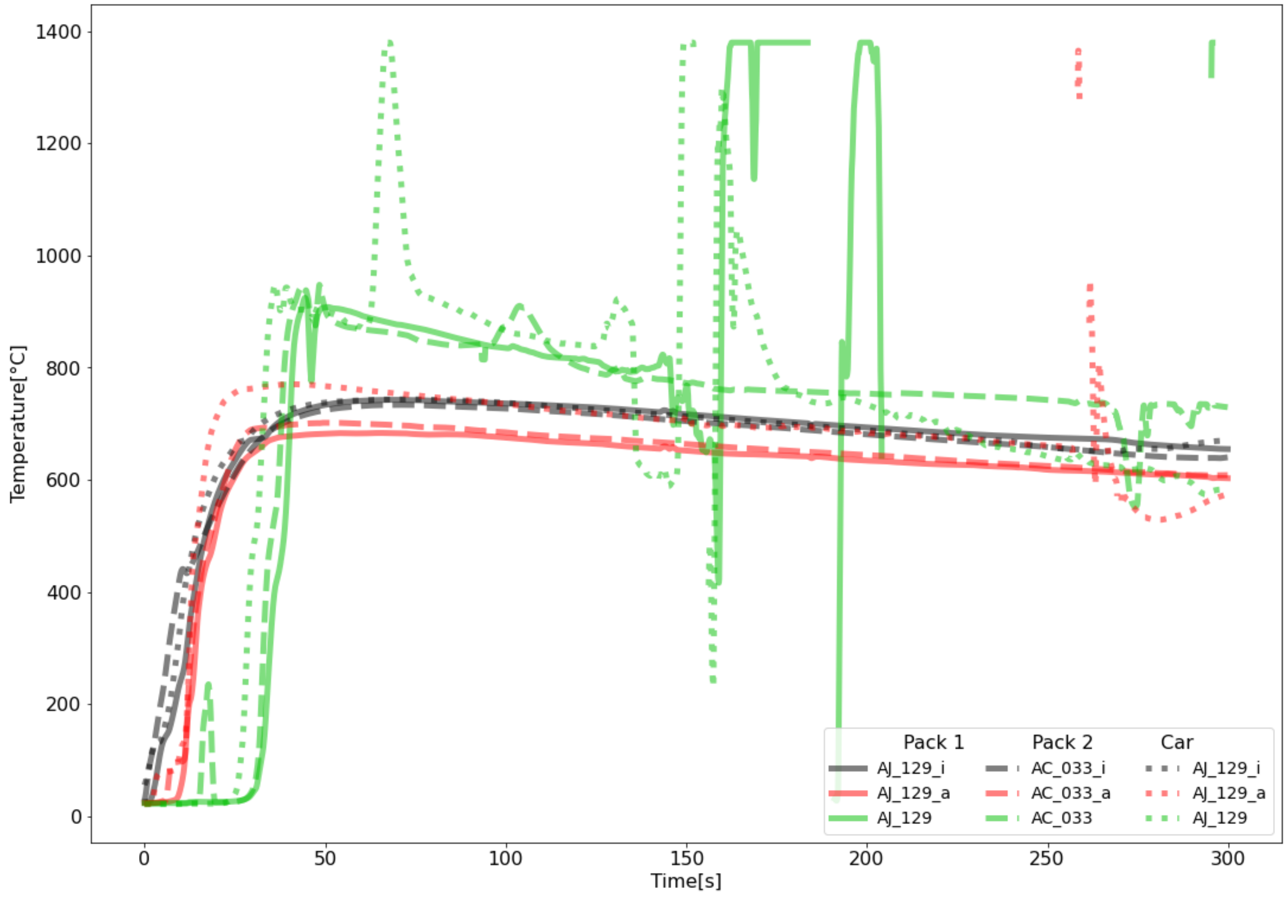


Thermal runaway propagation – Car A



TP is faster in a car possibly due to less heat dissipation and better gas tightness of a pack installed in a vehicle – role of vented gases in TP!

Thermal runaway propagation – Car A



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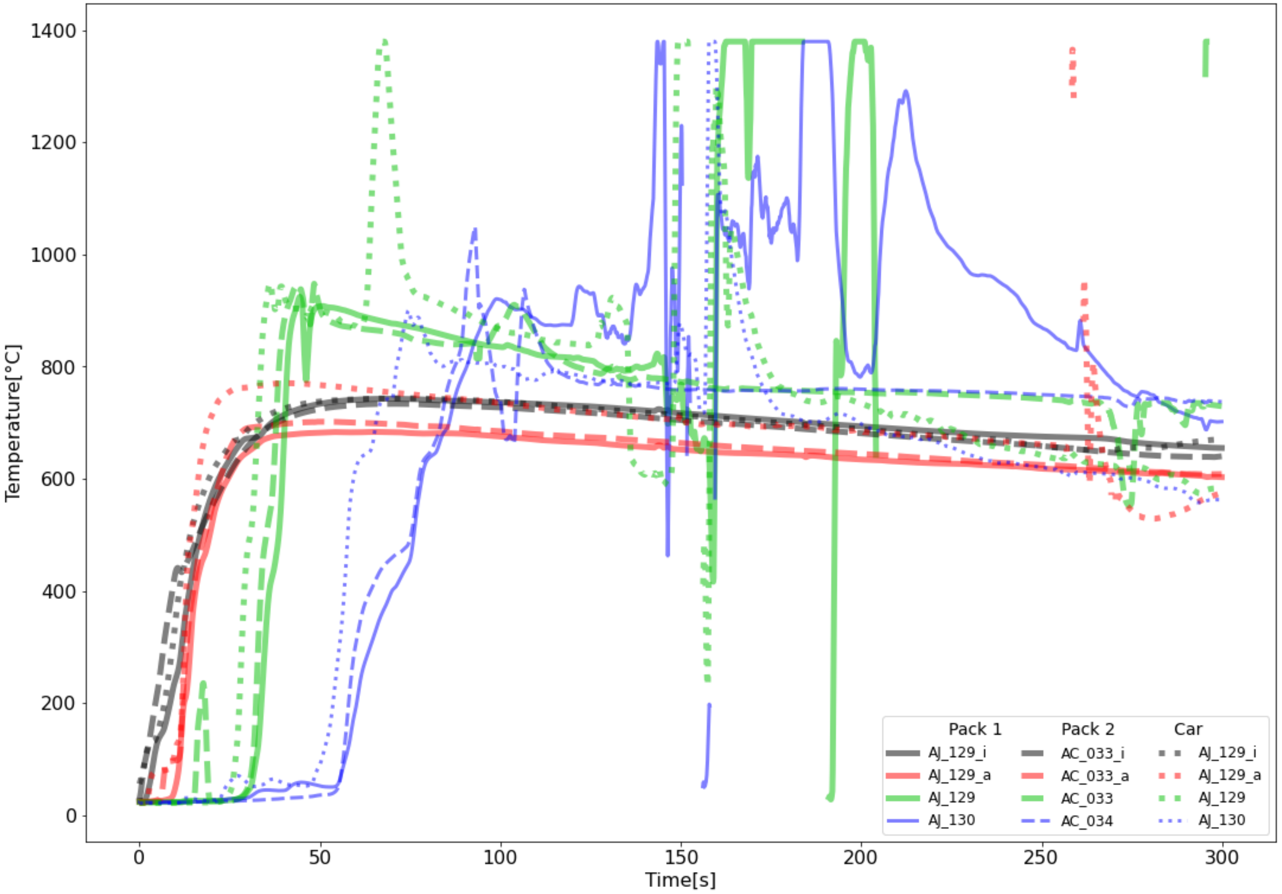
Thermal runaway propagation – Car A



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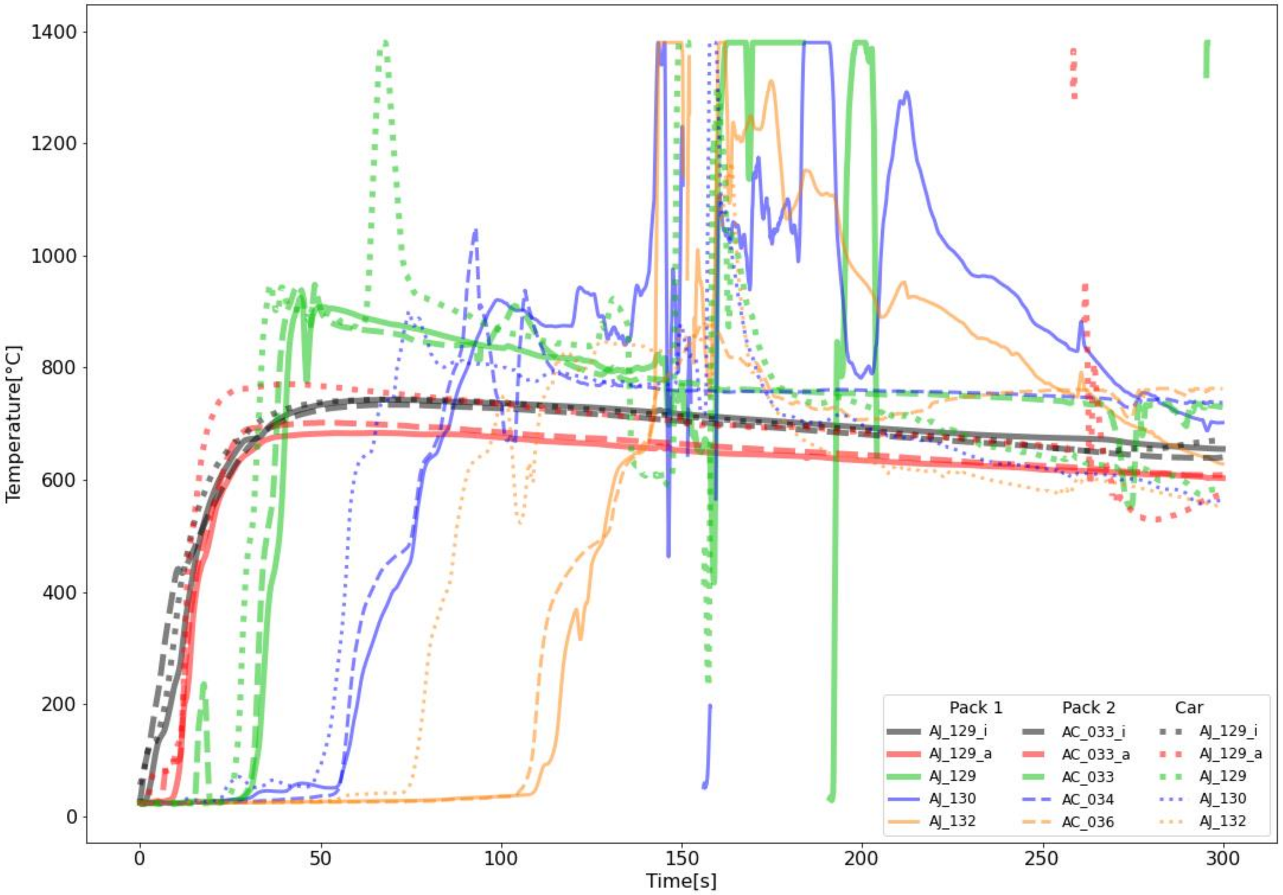
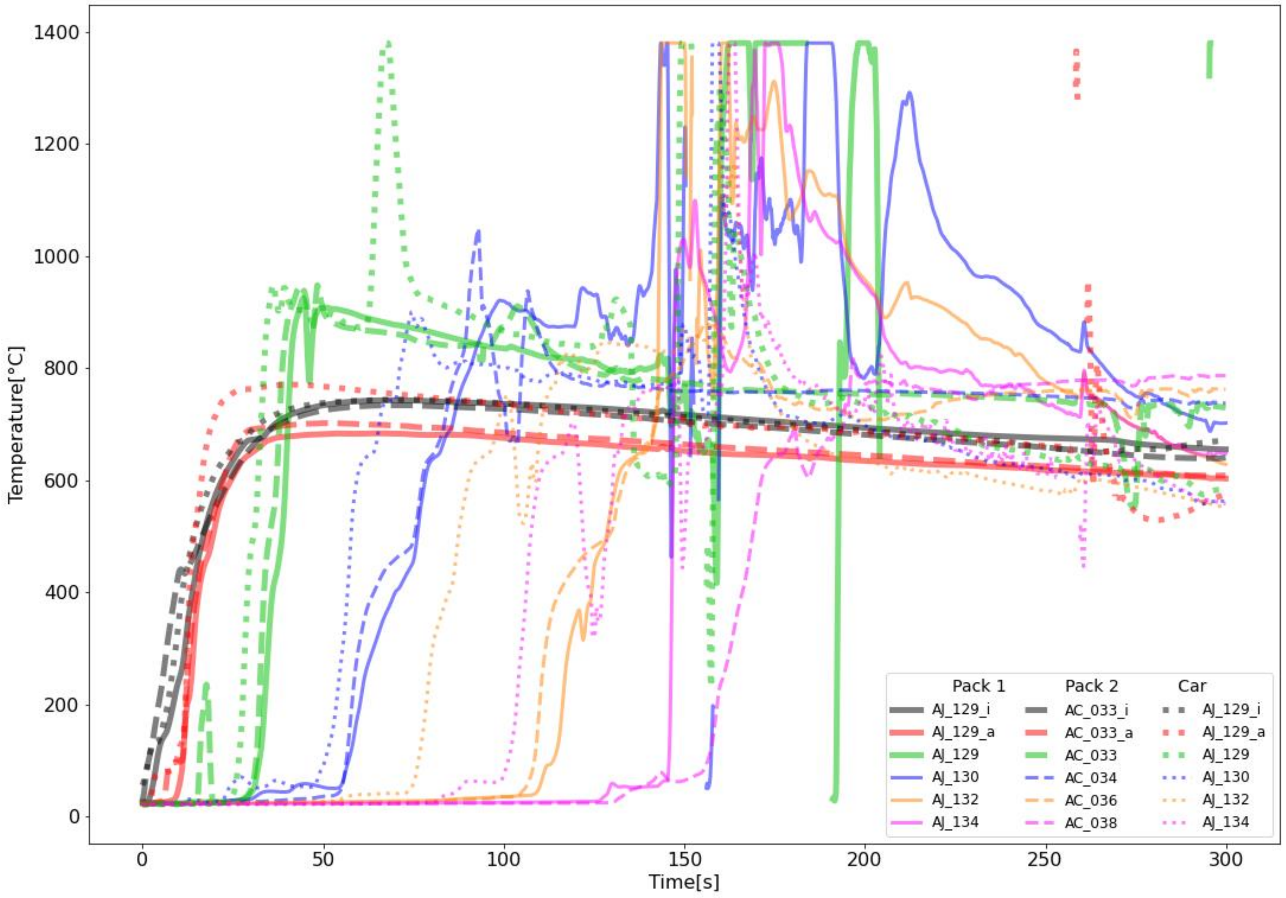
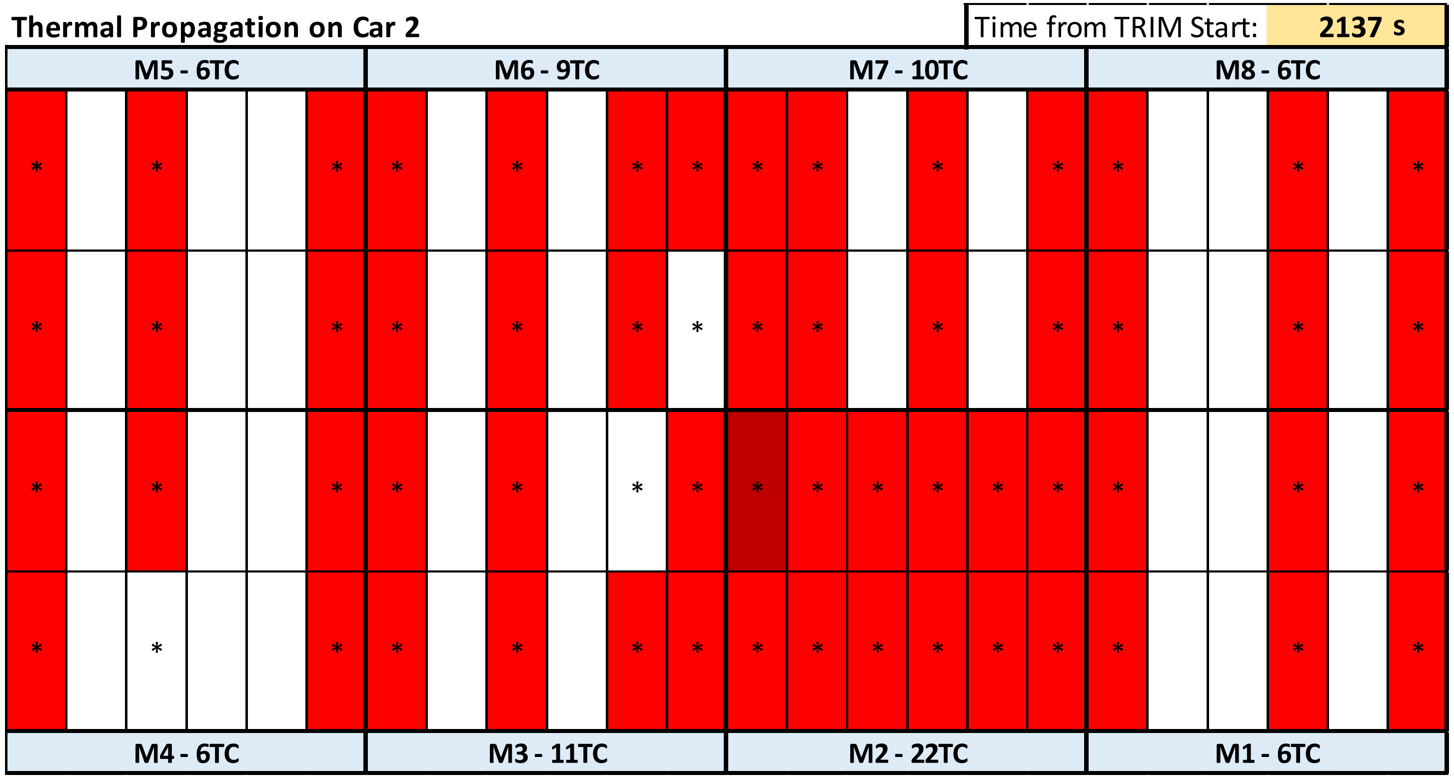
Thermal runaway propagation – Car A



Thermal runaway propagation – Car A



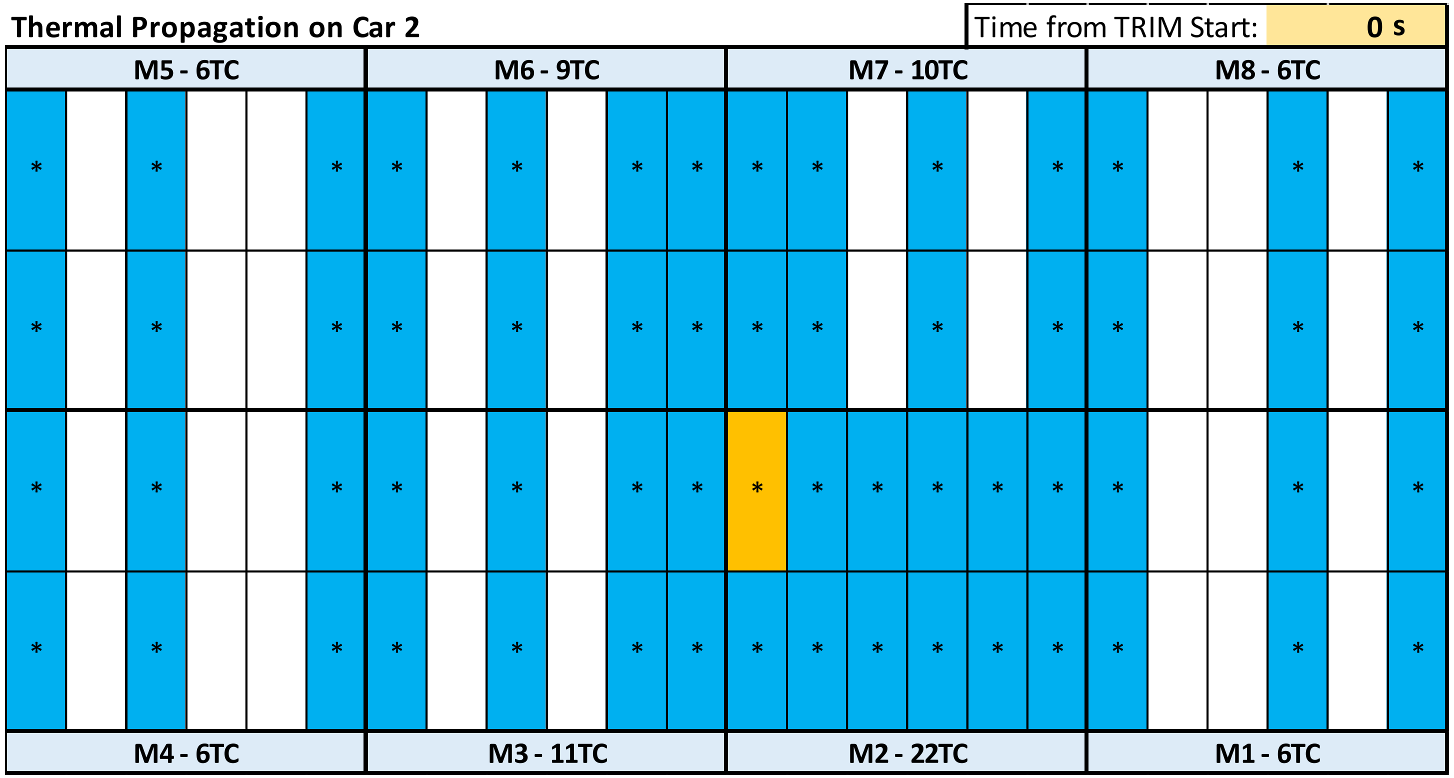
Thermal Propagation Car B



Also for this system hot vented gases play an important role in the heat transfer and, hence, in TP

Cell turns red when its temperature exceeds 200°C

Thermal Propagation Car B

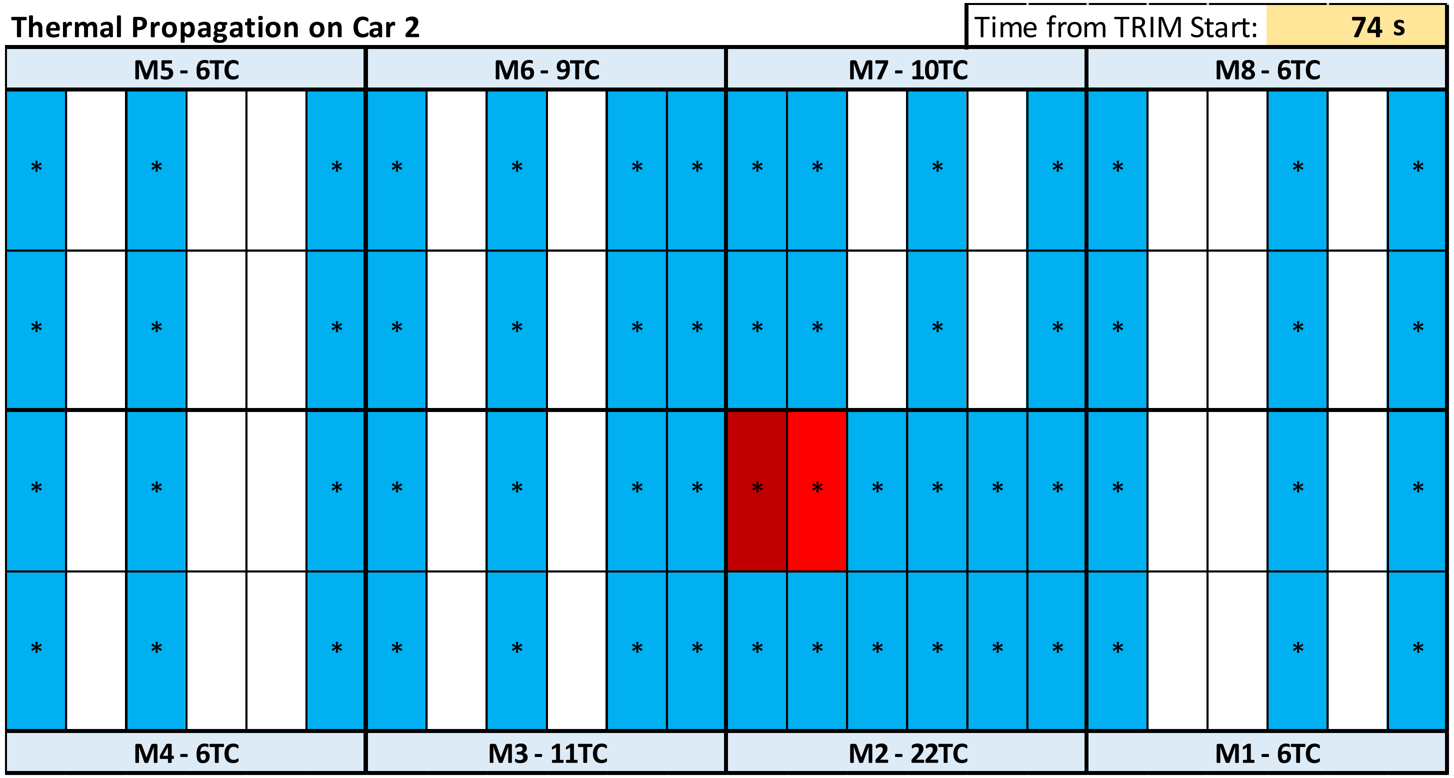


Thermal Propagation Car B

Thermal Propagation on Car 2 — Time from TRIM Start: **73 s**

M5 - 6TC						M6 - 9TC						M7 - 10TC						M8 - 6TC					
*		*			*	*		*		*	*	*	*		*		*	*			*		*
*		*			*	*		*		*	*	*	*		*		*	*			*		*
*		*			*	*		*		*	*	*	*	*	*	*	*	*			*		*
*		*			*	*		*		*	*	*	*	*	*	*	*	*			*		*
M4 - 6TC						M3 - 11TC						M2 - 22TC						M1 - 6TC					

Thermal Propagation Car 2

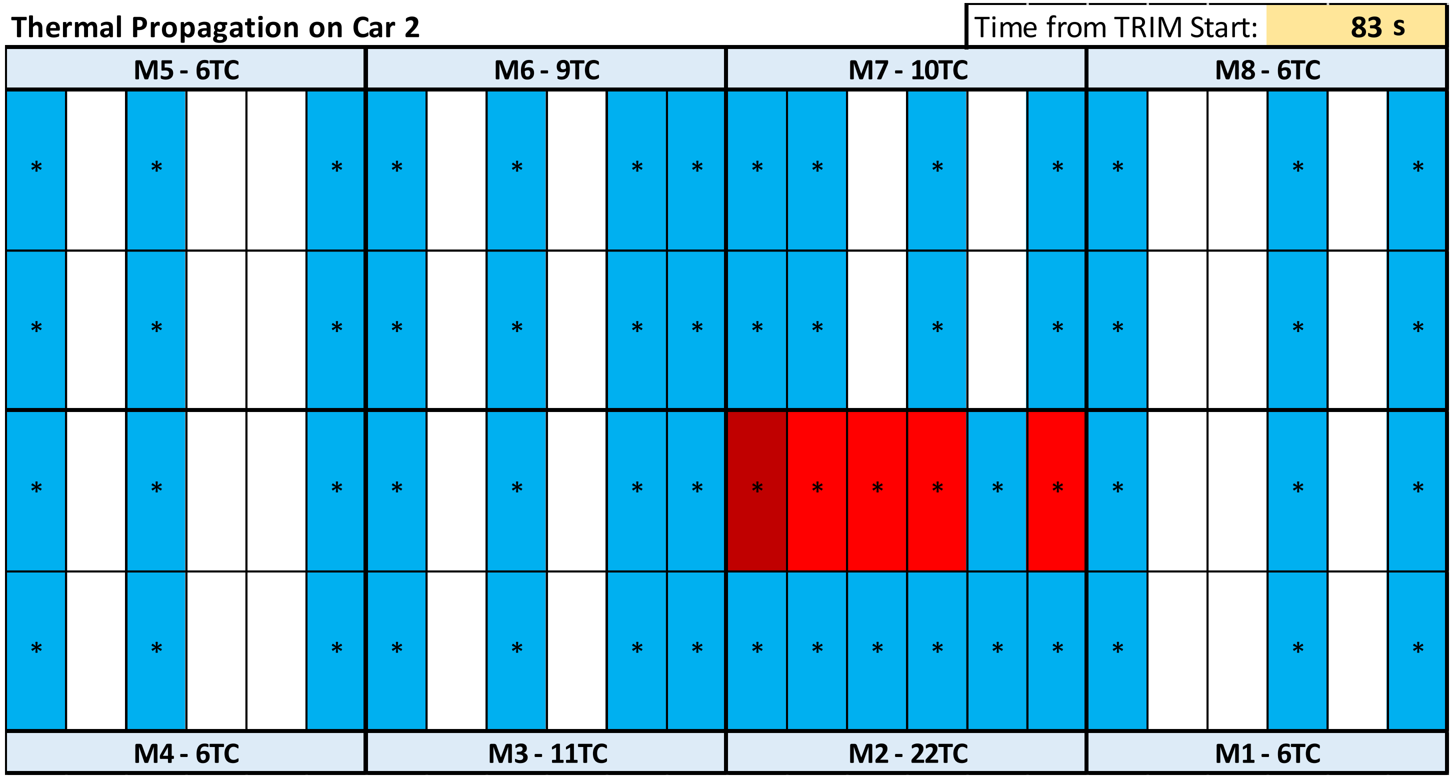


Thermal Propagation Car 2

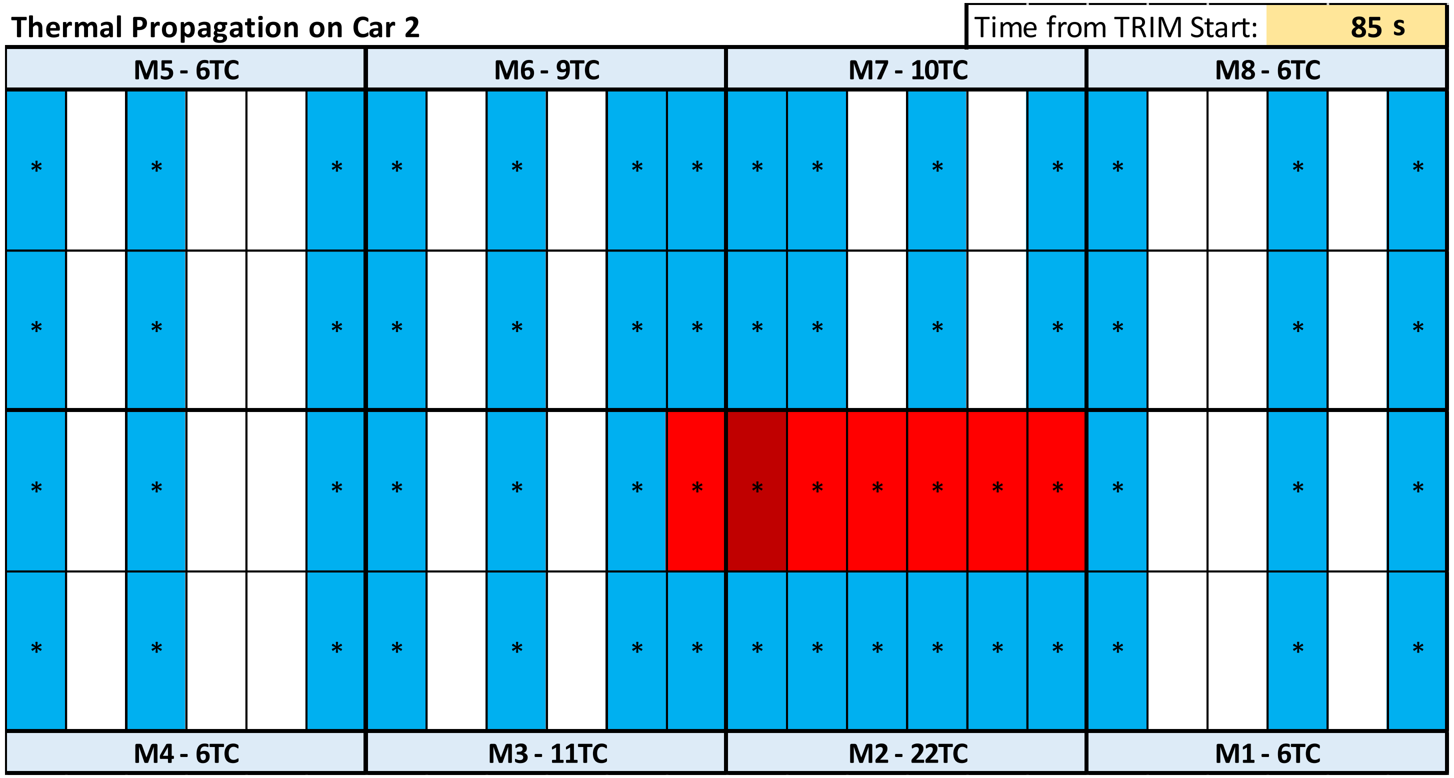
Thermal Propagation on Car 2 — Time from TRIM Start: **76 s**

M5 - 6TC						M6 - 9TC						M7 - 10TC						M8 - 6TC					
*		*			*	*		*		*	*	*	*		*		*	*			*		*
*		*			*	*		*		*	*	*	*		*		*	*			*		*
*		*			*	*		*		*	*	*	*	*	*	*	*	*			*		*
*		*			*	*		*		*	*	*	*	*	*	*	*	*			*		*
M4 - 6TC						M3 - 11TC						M2 - 22TC						M1 - 6TC					

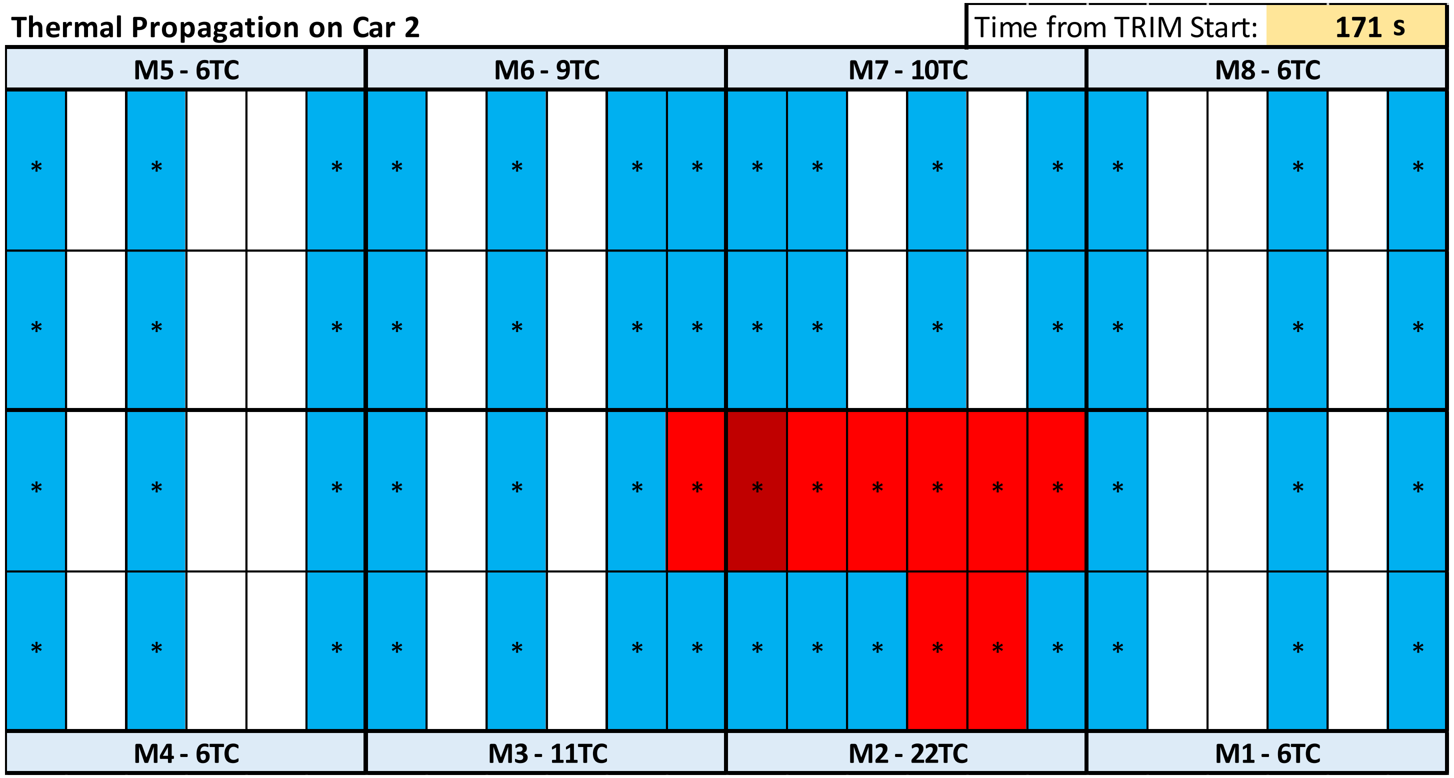
Thermal Propagation Car 2



Thermal Propagation Car 2



Thermal Propagation Car 2



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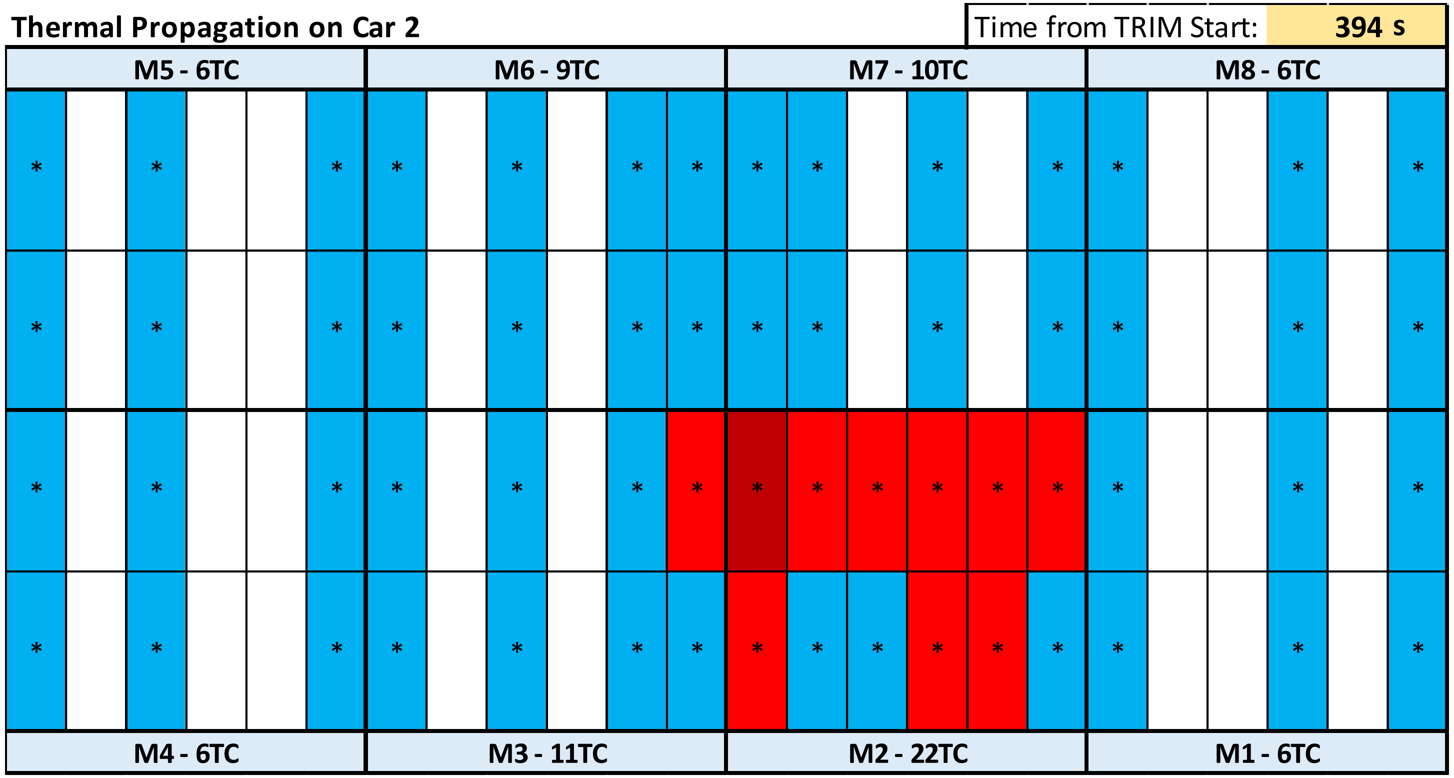
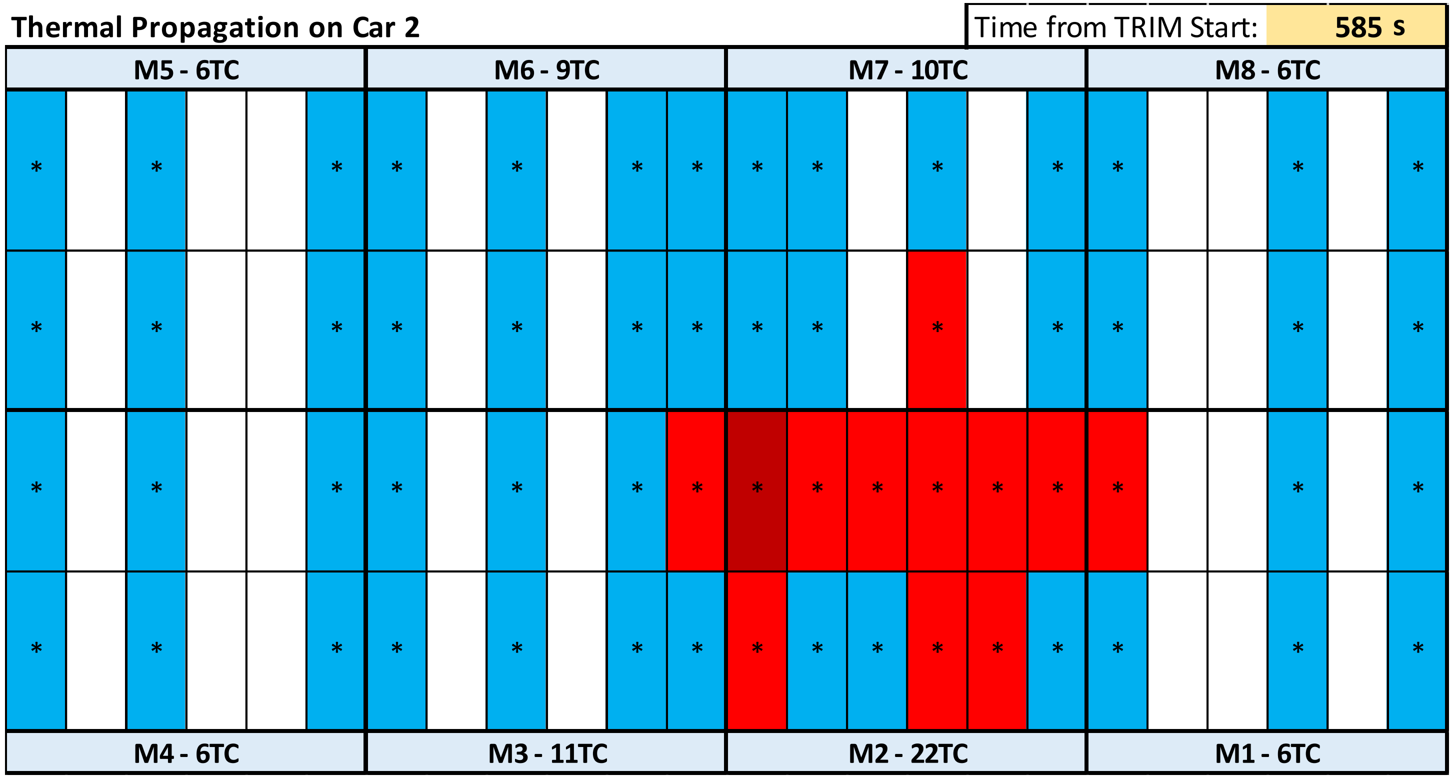


Thermal Propagation Car 2



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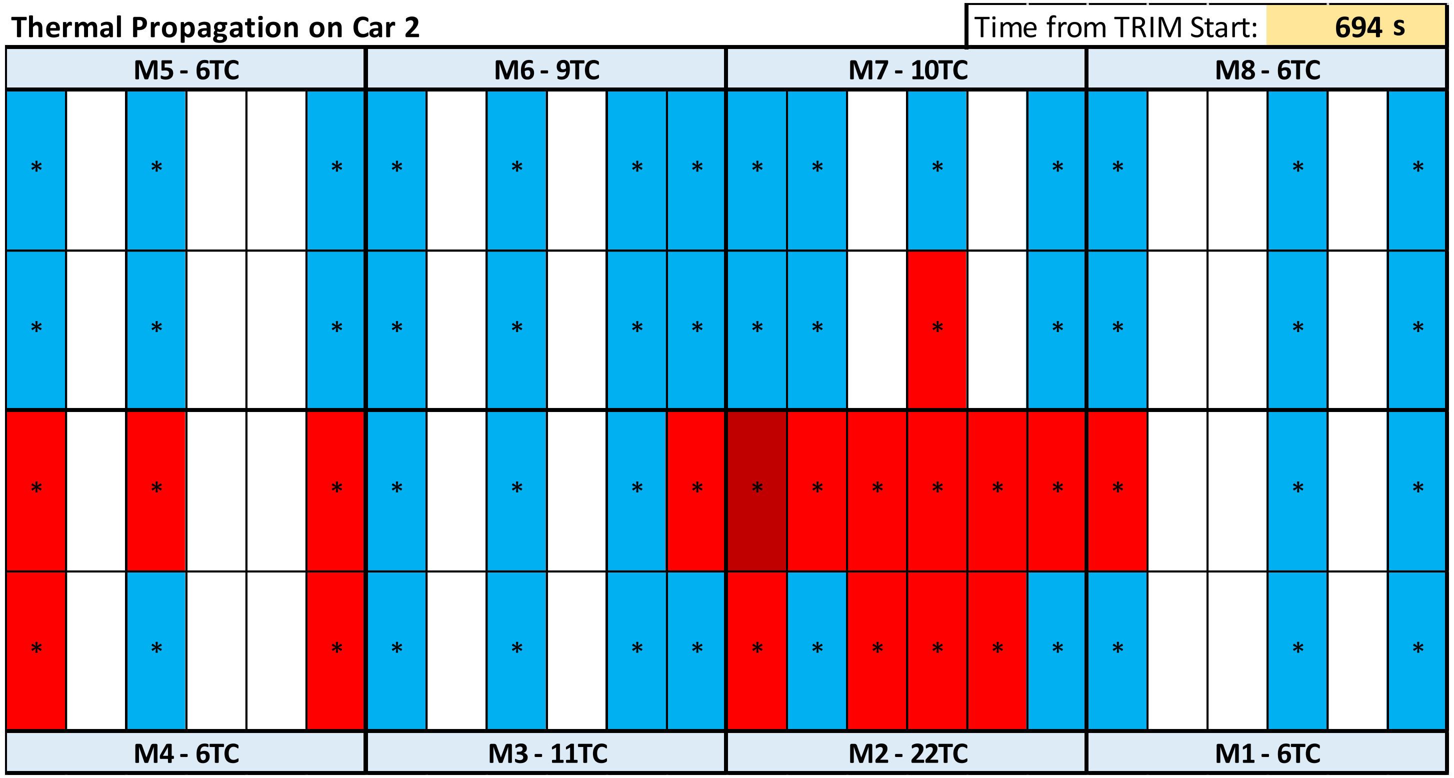
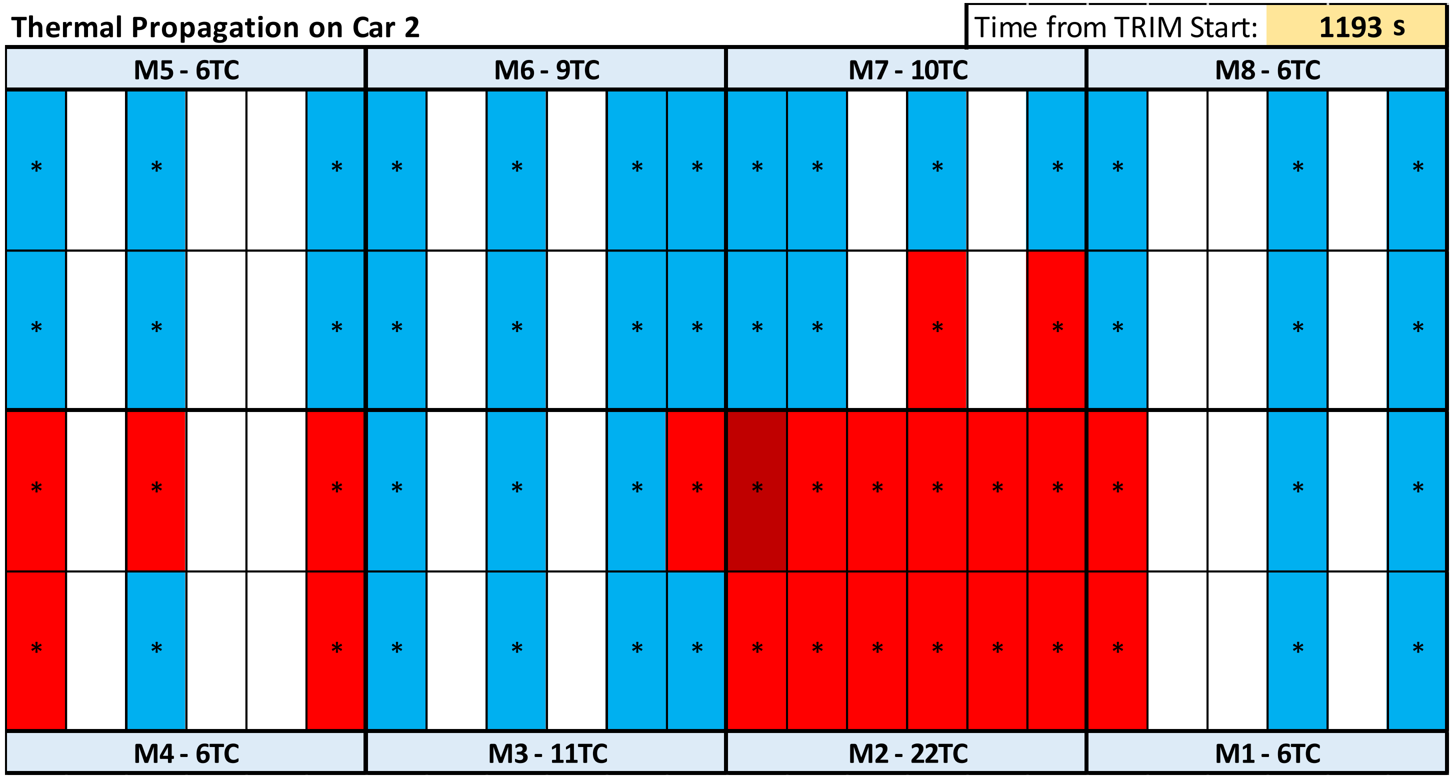
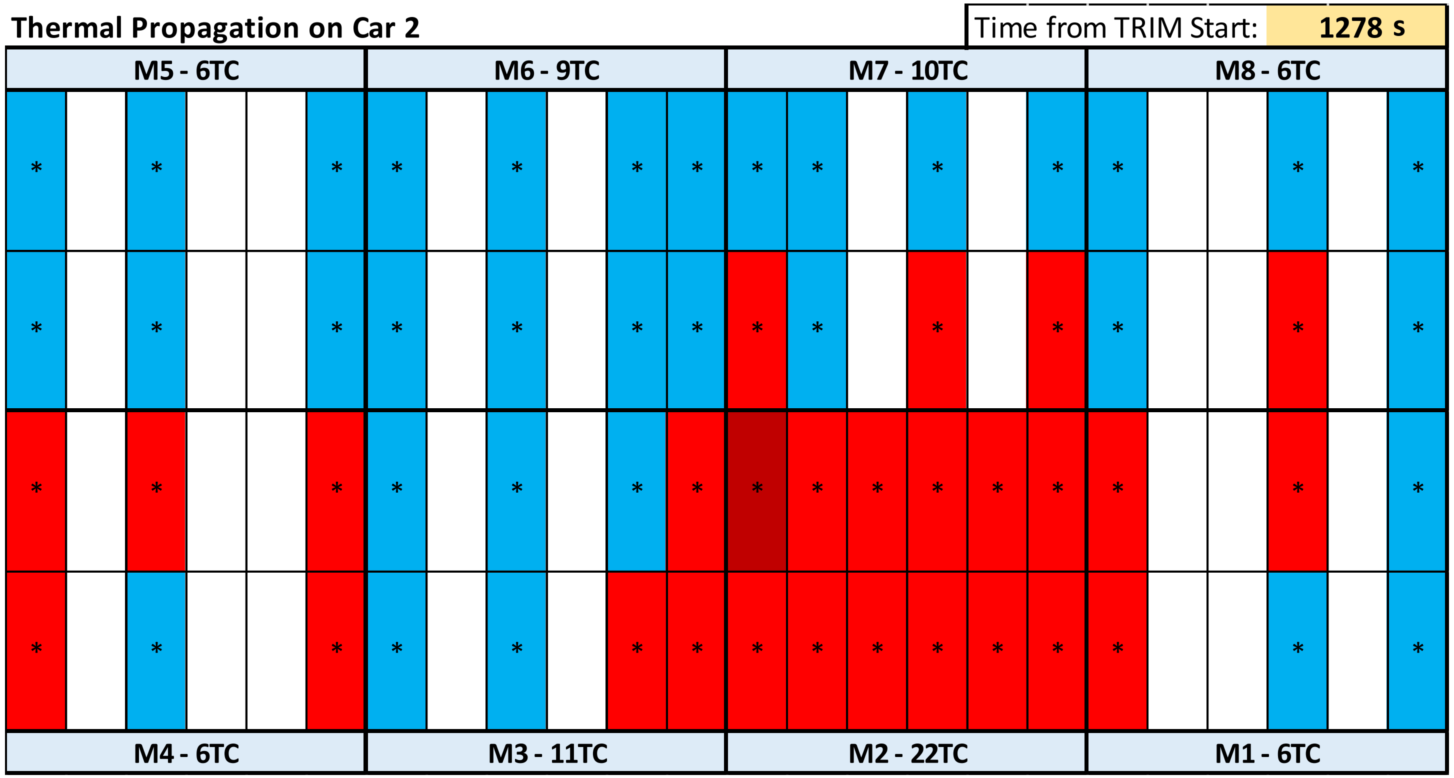


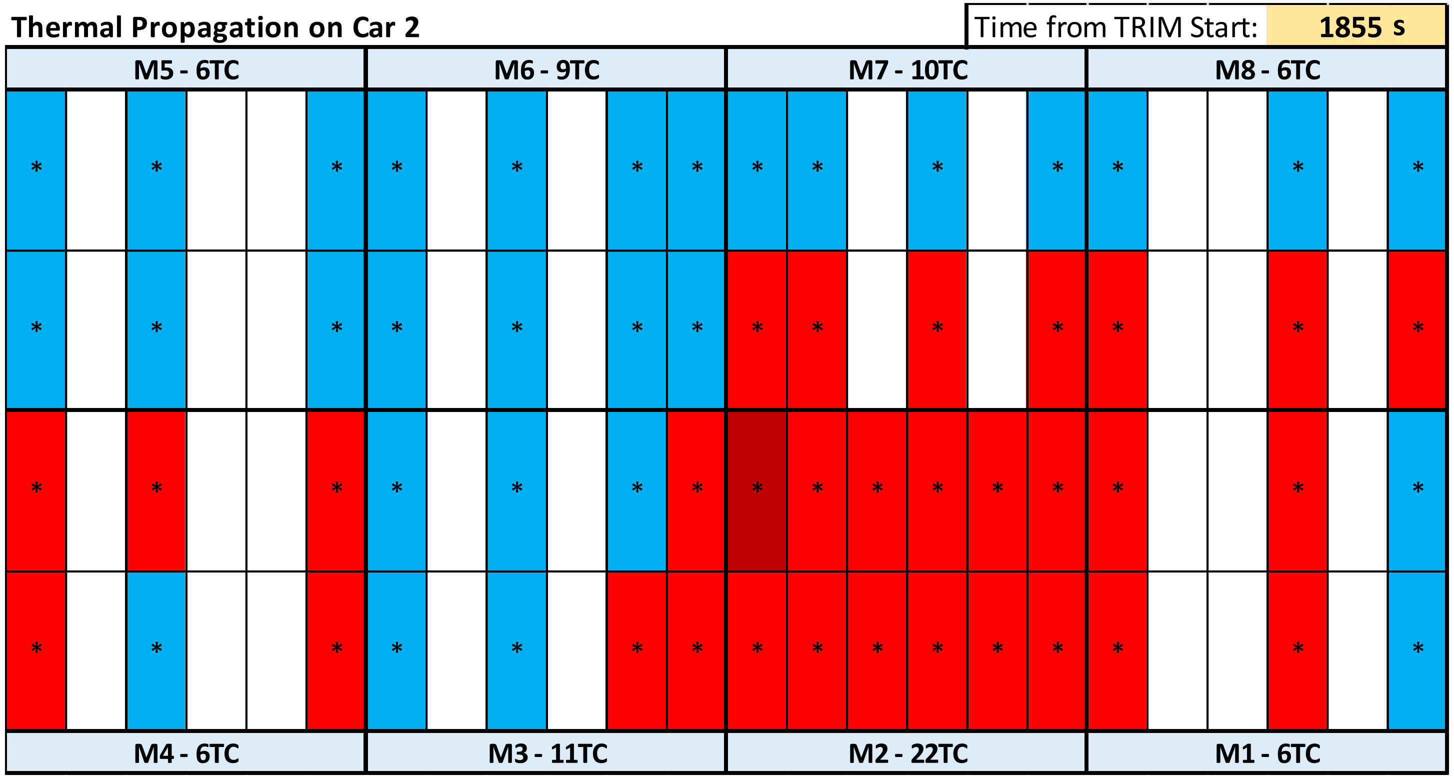
Thermal Propagation Car 2



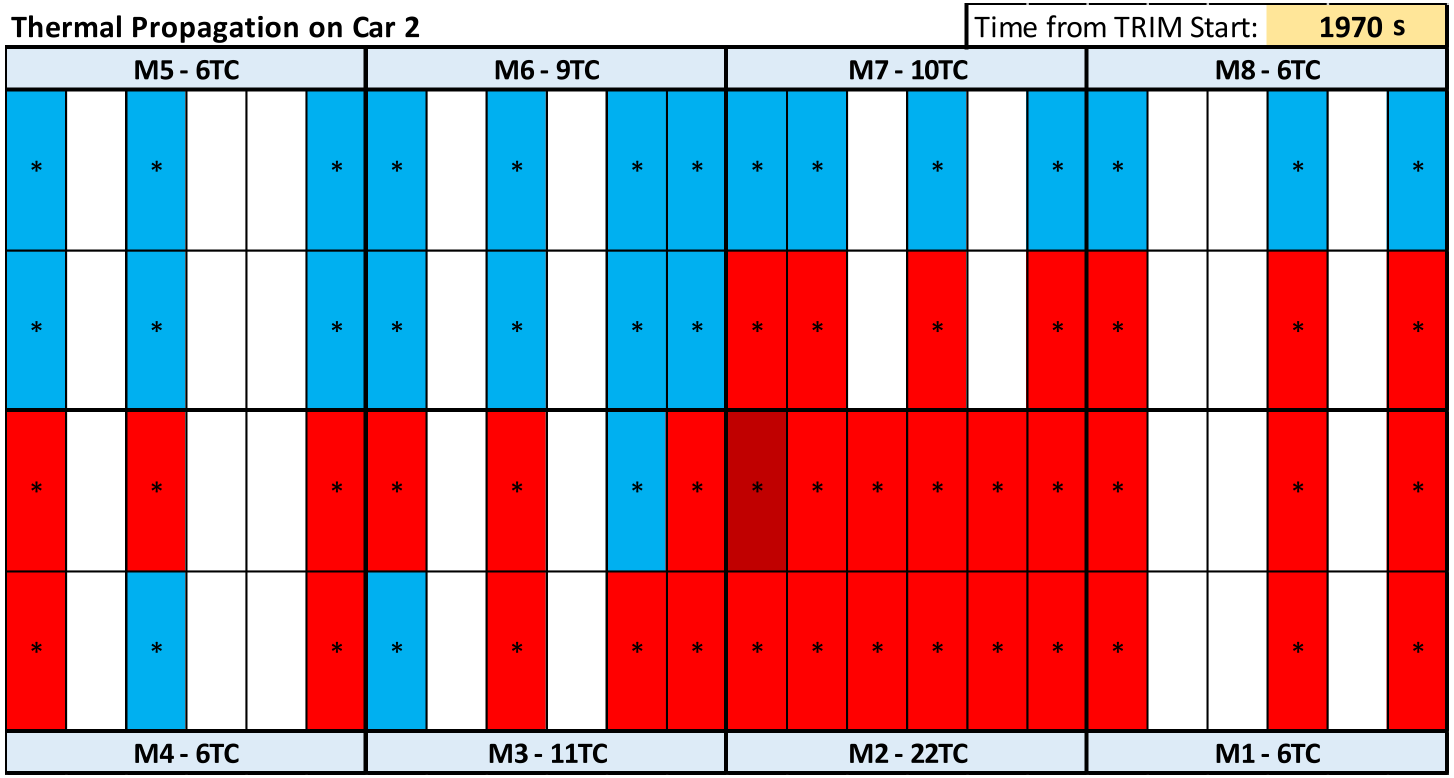
Thermal Propagation Car 2



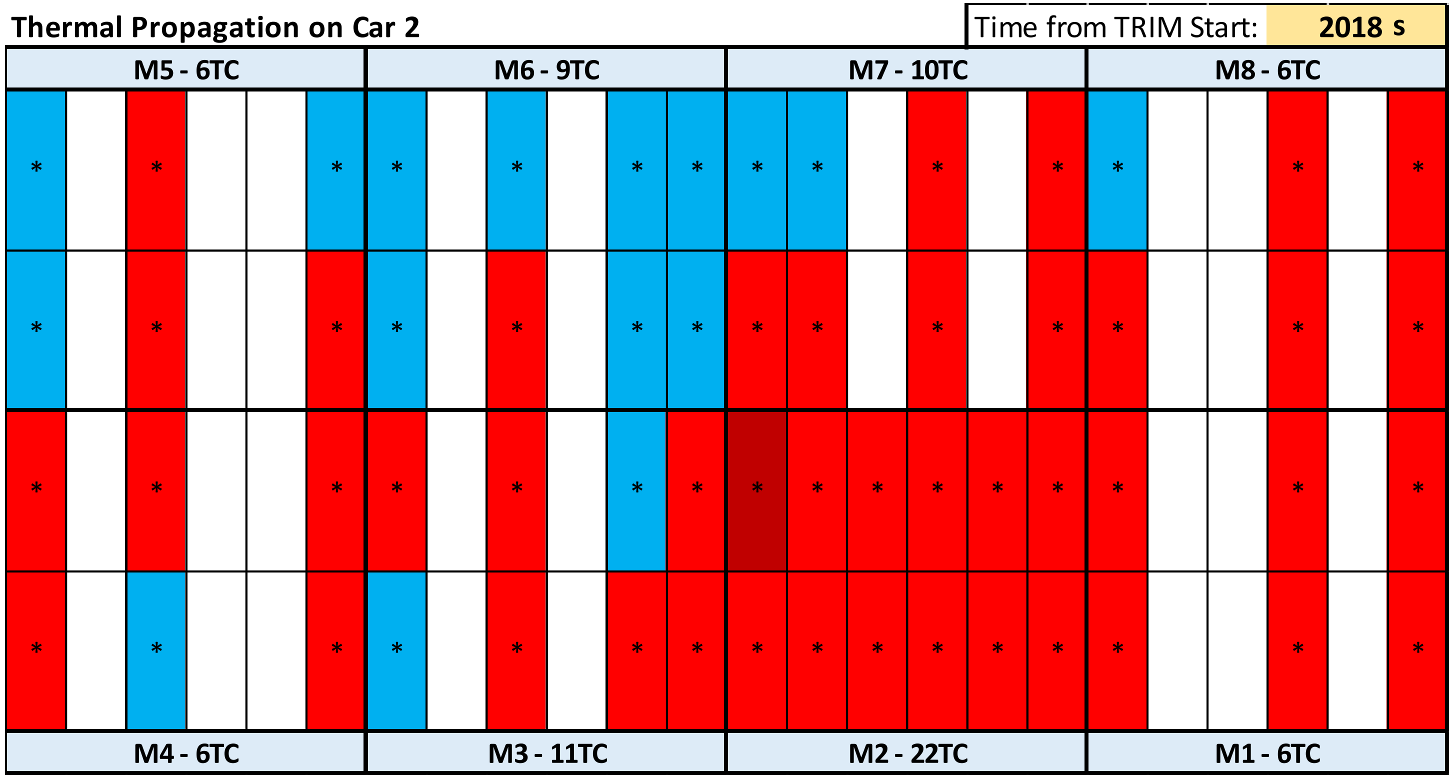
Thermal Propagation Car 2



Thermal Propagation Car 2



Thermal Propagation Car 2



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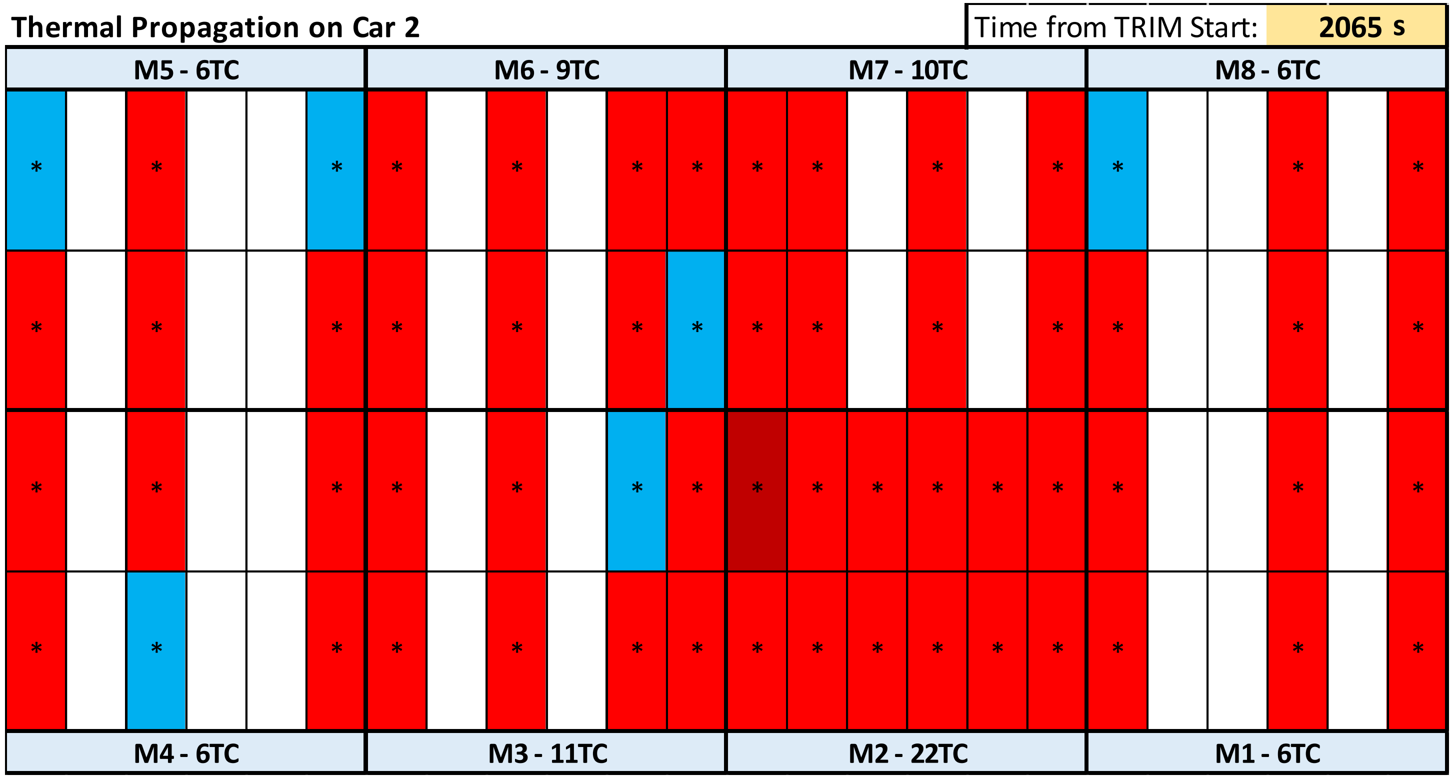
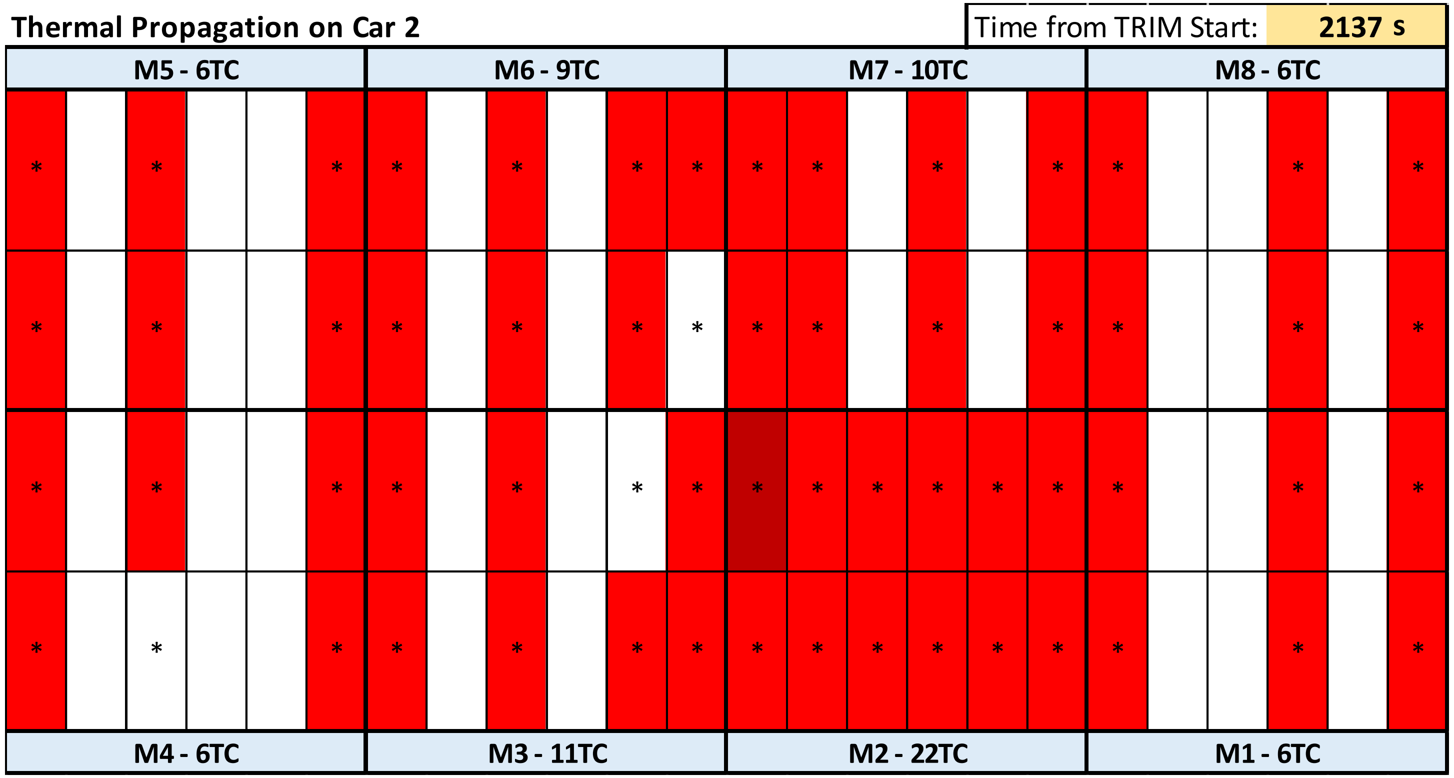
Thermal Propagation Car 2



Thermal Propagation Car 2



Thermal runaway propagation

JRC research has shown that:

- Hot vented gases play an important role in TP in both systems (type A and B) leading to “non-sequential” propagation patterns, different from those expected for a process governed by the heat conduction alone. This finding is in a agreement with previously published literature results.

- For DUTs of type A, TP was found to occur faster in a car possibly due to less heat dissipation and better gas tightness of a pack installed in a vehicle, underlining the role of hot vented gases in the overall heat transfer during the TP.

- For DUTs of type A, initial stages of TP at pack level were found to be reproducible.

Summary – general points

- Thermal runaway propagation tests at pack and vehicle levels are feasible.
- Thermal runaway was successfully and reliably initiated in all experiments at pack and vehicle levels using a rapid heater V5 developed by NRC Canada. No heater failures were observed.
- Vehicles with instrumented packs functioned normally (no errors).
- Thermal runaway initiation at pack and vehicle levels using a rapid heater V5 was reproducible for tested DUTs of type A.
- The energy added through heating was 1.3% - 3.2% of the electric cell energy, repeatable among the experiments performed at different DUT complexity levels and different laboratories.

Summary – TR criteria

- TR criteria as currently defined in the GTR EVS text can detect TR, but in some cases lead to a delayed detection of TR.

- Voltage drop does not seem to be a reliable indicator of TR in systems with parallel-connected cells. For DUTs of type A in our study, the voltage drop value (to 75%, to 50% or to 25% of the initial value) was of no noticeable significance when determining the time of meeting the criteria. This is in agreement with the JRC's analysis of TR criteria at single cell level (see e.g. EVS22-E1TP-0200 [EC]Thermal runaway criteria.pdf)

- In our experiments, criteria like heater power, pressure change rate in a pack and smoke external to the DUT could detect TR, in some cases even earlier than the criteria based on T_{cell}, dT_{cell}/dt and voltage drop.

Summary – TP

- Hot vented gases play an important role in TP in both systems (type A and B) leading to “non-sequential” propagation patterns, different from those expected for a process governed by the heat conduction alone. This finding is in a agreement with previously published literature results.

- For DUTs of type A, TP was found to occur faster in a car possibly due to less heat dissipation and better gas tightness of a pack installed in a vehicle, underlining the role of hot vented gases in the overall heat transfer during the TP.

- For DUTs of type A, initial stages of TP at pack level were found to be reproducible.

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Thank you

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