Design Fire Scenarios for Hazard Assessment of Modern Passenger Vehicles

JONATHAN HODGES, PHD | JULY 2025

About the Presenter

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- Manages Blacksburg, VA office near Virginia Tech
- Leads modeling service line in RDT&E at Jensen Hughes
- Research focuses on fire dynamics, modeling, and artificial intelligence
- Member of the SFPE Foundation Board of Governors
- Member of SFPE task groups on model substantiation and local fire exposures
- Contributor to Fire Dynamics Simulator (FDS) with a focus on fire growth and validation

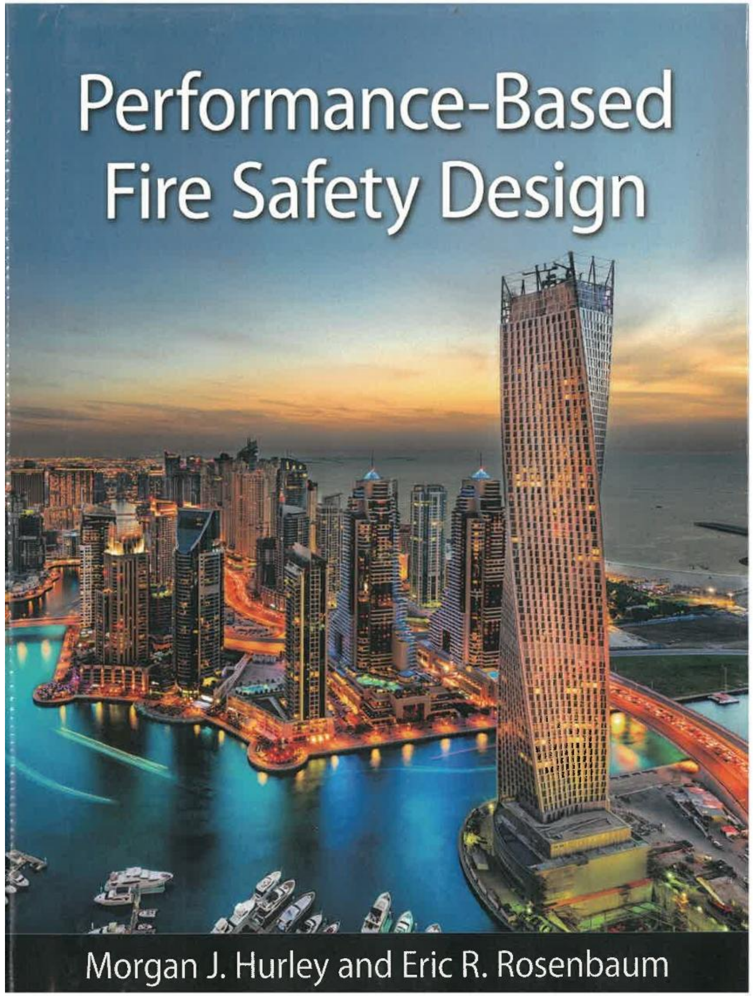
Outline

- What is a fire scenario?
- Passenger vehicle heat release rates
- Passenger vehicle productions of combustion
- Additional considerations in performance-based design

What is a Fire Scenario? – Definition

- A set of conditions that defines the development of fire and the spread of combustion products throughout a building or portion of a building, the reactions of people to fire, and the effects of combustion productions.

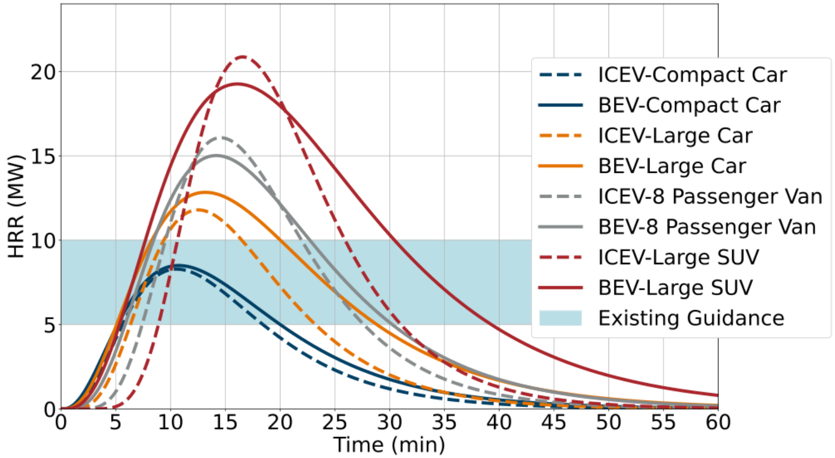
Rosenbaum 2007, *SFPE Engineering Guide to Performance-Based Fire Protection*
https://www.sfpe.org/publications/resources/pbdguide



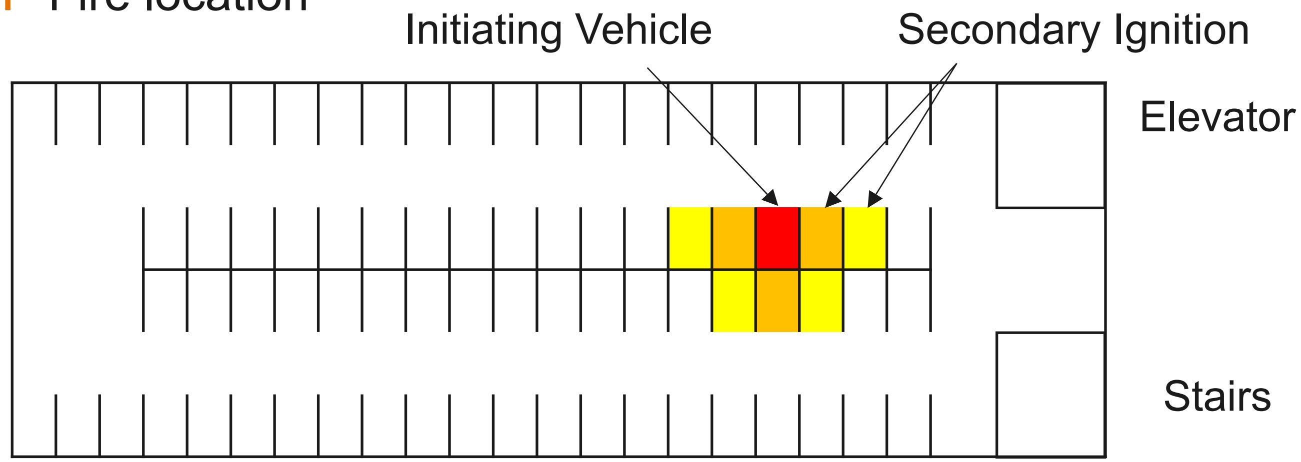
What is a Fire Scenario? – In Practice

+ Description of fire progression listing assumptions, limitations, and technical basis

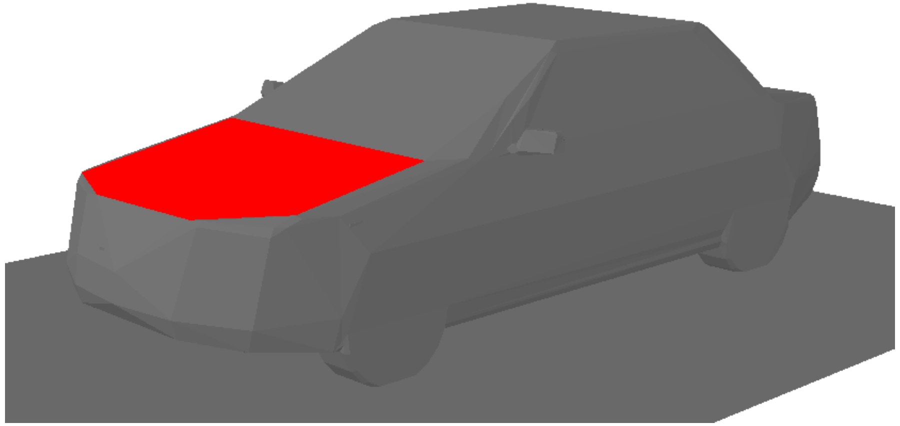
+ Fire size (heat release rate with time)



+ Fire location



+ Fire diameter / model representation



+ Combustion reaction (N-Octane in table)

Parameter	Value	Units
Fuel Reactant	C8H18	
Soot yield	0.038	g/gfuel
CO yield	0.011	g/gfuel
Heat of combustion	44.5	MJ/kg
Radiative fraction	0.40	-

What is a Fire Scenario? – In Practice

+ Description of fire progression listing assumptions, limitations, and technical basis

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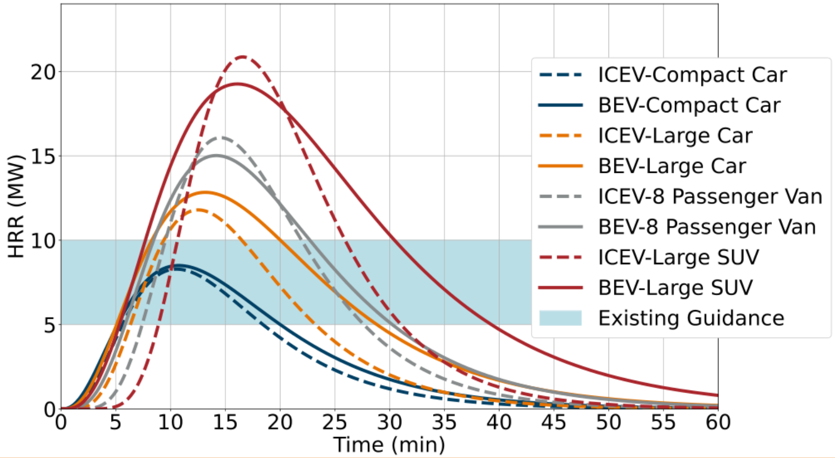
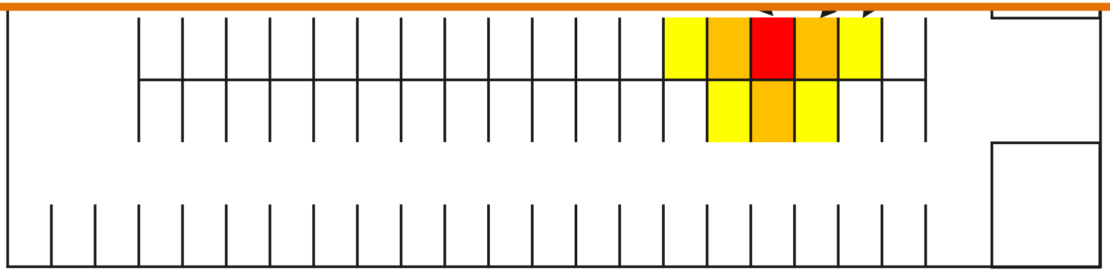


J.L. Hodges, U. Salvi, A. Kapahi, Design fire scenarios for hazard assessment of modern battery electric and internal combustion engine passenger vehicles, Fire Safety Journal 146 (2024) 104145. https://doi.org/10.1016/j.firesaf.2024.104145.



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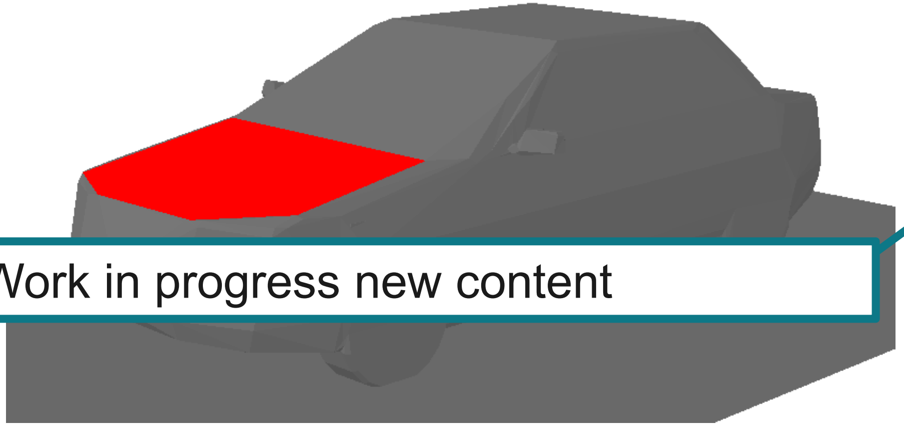

Work in progress new content

+ Combustion reaction (N-Octane in table)

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Heat Release Rate

+ Historical guidance
+ Research on modern vehicles
+ Experiments
+ Model development
+ Comparison with experiments
+ Comparison by fuel type

Heat Release Rate

- Historical guidance on passenger vehicles

Standard	Vehicle Type	HRR (MW)
NFPA 502	• 1 Passenger car • Multiple passenger cars	• 8 • 15
PIARC 05.05B	• 1 Small passenger car • 1 Large passenger car • 2-3 passenger cars • Van	• 2.5 • 5 • 8 • 15
NCHRP	• 1 Passenger car	• 1.5-9 (majority 5)

***NFPA 502 current edition, guidance not changed significantly since 2008.**
PIARC based on 1999 report
National Cooperative Highway Research Program 2011

Research on Modern Vehicles

Document	Findings
NFPA Research Foundation / Boehmer 2021, PIARC 2022R05	• Modern vehicles pose a distinct hazard due to increased combustible plastics and alternative propulsion systems.
Lecocq 2012	• Study on small BEVs vs. ICEVs of similar size showed similar peak HRR and Total Heat Released (THR).
Watanabe 2012	• Study indicating higher HRR for BEVs compared to ICEVs
Hynynen 2023	• Negligible differences in peak HRR and THR between small ICEVs and BEVs with sprinkler suppression
RISE / Willstrand 2020	• BEV higher HRR compared to ICEV of similar sized vans • Similar effective heat of combustion for both BEV and ICEV vans

Experiments

- Provide critical data for design
  - Individual experiments may not be conservatively boun
- Laboratory capabilities
  - Limited HRR which can be measured in a lab
- Probabilistic nature of failures
  - Vehicle fires have random elements
- Cost
  - High price per vehicle experiment

Need an approach to scale experimental measurements to be representative of conservatively bounding scenarios for design.

*Kang, S., Kwon, M., Yoon Choi, J. & Choi, S. Full-scale fire testing of battery electric vehicles. *Appl. Energy* **332**, 120497 (2023).

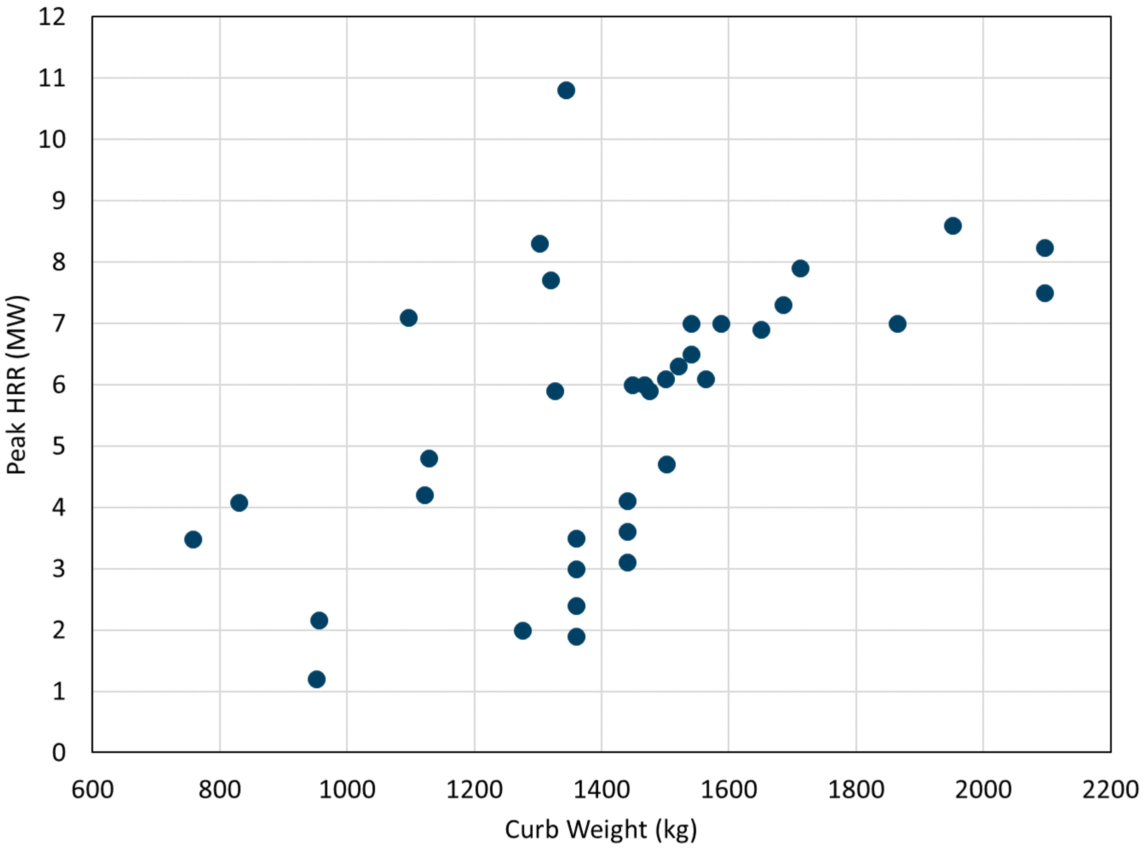
Dataset

- Total of 40 full-scale vehicle fires

Vehicle Type	ICEV	BEV	PHEV
Car	18	10	2
Van	4	2	0
SUV	0	3	0

- Data
  - Energy capacity (fuel tank, battery capacity)
  - Curb weight
  - Consumed mass fraction
  - Peak heat release rate
  - Total heat released

Scaling HRR with Vehicle Size



*Hodges, J. L., Salvi, U. & Kapahi, A. Design fire scenarios for hazard assessment of modern battery electric and internal combustion engine passenger vehicles. *Fire Safety Journal.* **146**, (2024).

Peak HRR Calculation

+ Linear combination of individual components

$$\dot{Q}_{max} = \dot{Q}_{bat} + \dot{Q}_{veh} + \dot{Q}_{gas}$$

+ $\dot{Q}_{bat}$ from electrical energy capacity

$$\dot{Q}_{bat} = 0.16 \times E_{elec}^{0.67}$$

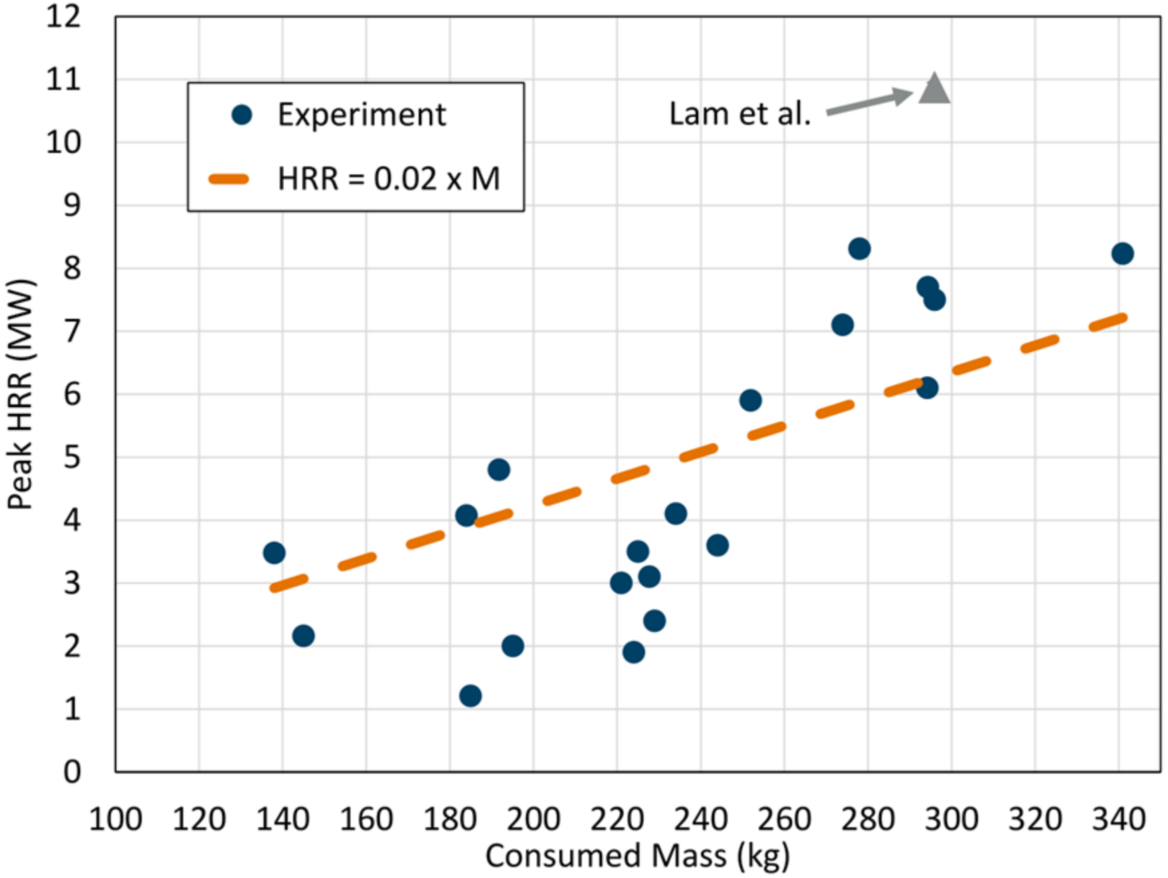
+ $\dot{Q}_{gas}$ from gas quantity over fixed duration

$$\dot{Q}_{gas} = \frac{m_{gas}\,\Delta H_{c,gas}}{\Delta t}$$

+ $\dot{Q}_{veh}$ linearly scaled based on consumed mass

$$\dot{Q}_{veh} = \frac{\dot{Q}_{veh,ref}}{m_{c,veh,ref}}\, m_{c,veh,}$$

Scaling HRR with Fraction of Mass Lost



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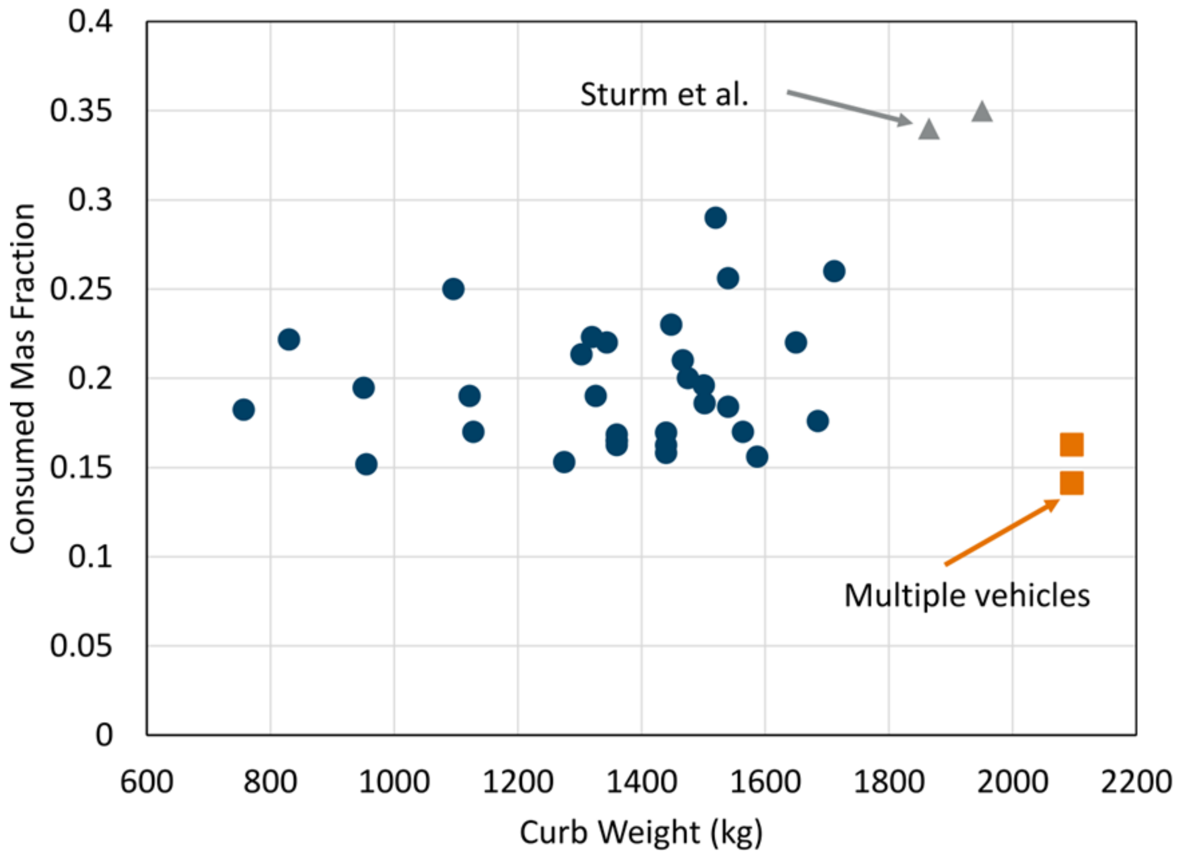
Peak HRR Calculation

+ High variability in consumed mass fraction
+ No consistent trend with vehicle size
+ Two values statistically determined
  - 17% – HRRs with best fit to the data
  - 25% – Conservatively bounding HRRs

Relationship Between Mass Loss Fraction and Vehicle Size



Conservatively bounding will be defined and discussed later in this talk.

*Hodges, J. L., Salvi, U. & Kapahi, A. Design fire scenarios for hazard assessment of modern battery electric and internal combustion engine passenger vehicles. *Fire Safety Journal.* **146**, (2024).

Total Heat Released

+ Linear combination of individual components

$$E_{tot} = E_{bat} + m_{c,veh}\Delta H_{c,veh} + m_{c,gas}\Delta H_{c,gas}$$

+ E_{bat} from electrical energy capacity

$$E_{bat} = 48.5 \times E_{elec}$$

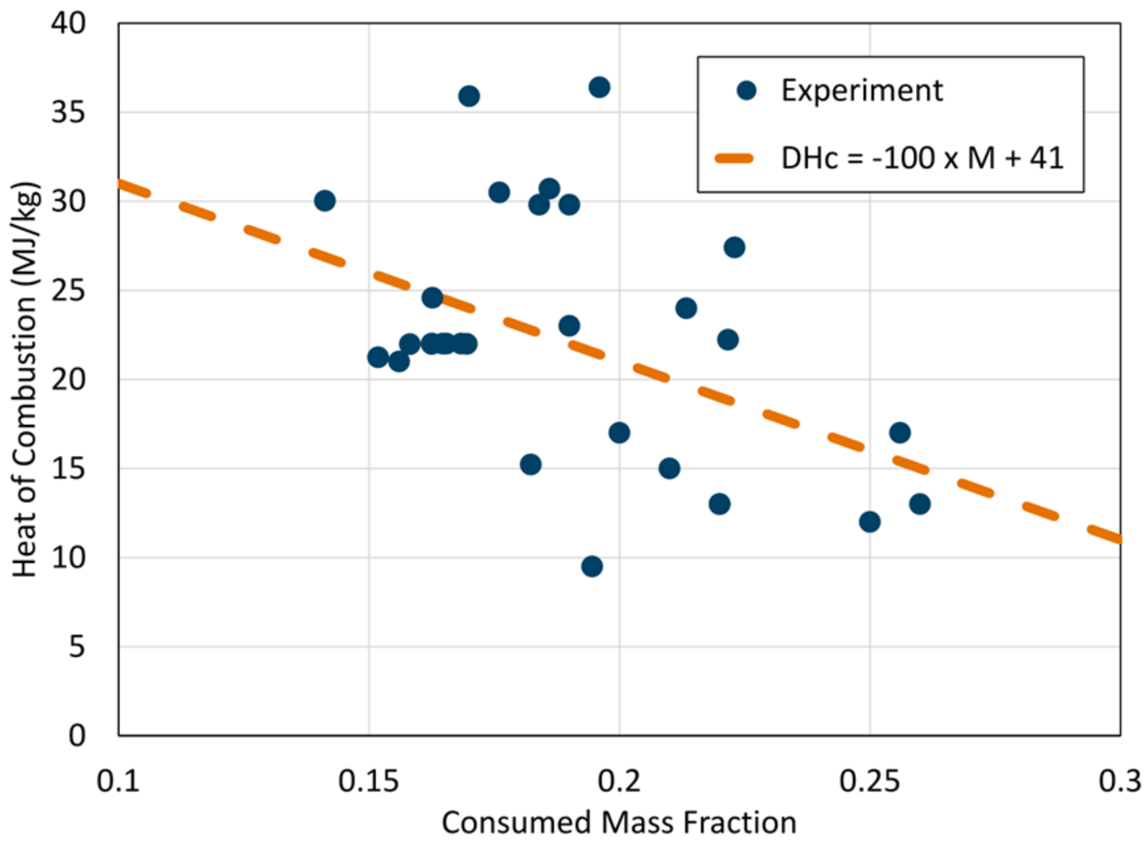
+ E_{gas} from gas quantity and heat of combustion

$$E_{gas} = 44.1 \times m_{gas}$$

+ E_{veh} from consumed mass fraction, curb weight, and heat of combustion

$$\mathrm{E_{veh}} = \Delta H_{c,veh} m_{c,veh}$$

$$\Delta H_{c,veh} = -100 \times M + 41$$



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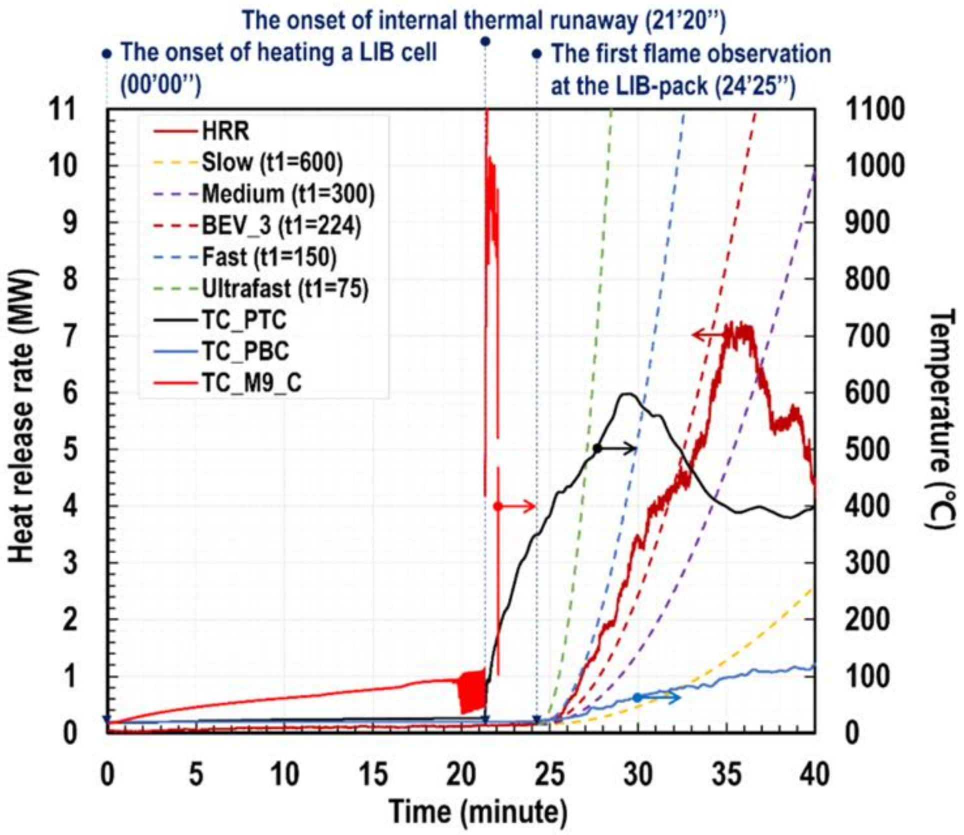
Time to Peak Heat Release Rate

+ t-squared fire growth

$$\dot{Q} = \alpha t^2$$

+ Variability across tests
  - Long incipient stage
  - Different ignition strategies
  - Time at which battery or fuel tank becomes involved

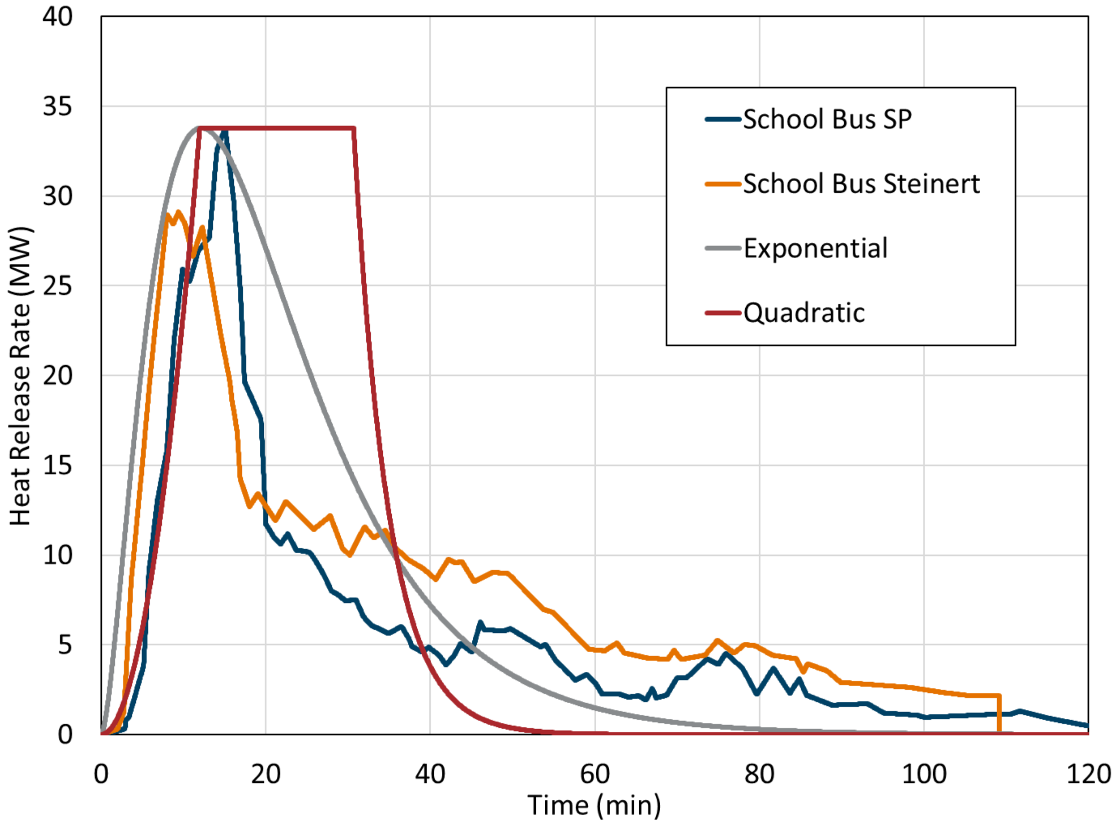
+ Assumed medium-fast growth
  - Time to 1.055 MW of 3.75 minutes (225 seconds)
  - Aligned with majority of test data



*Kang, S., Kwon, M., Yoon Choi, J. & Choi, S. Full-scale fire testing of battery electric vehicles. *Appl. Energy* **332**, 120497 (2023).

Time-Resolved Profile

- Overview
  - Rapid growth to peak
  - Short duration at peak
  - Slow decay
- Exponential Representation
  - $Q(t) = f(Q_{max}, t_{max}, E_{tot})$



$$Q(t) = \dot{Q}_{max}\, nr\left(1 - e^{-kt}\right)^{n-1} e^{-kt}$$
$$n = 0.7429\, e^{2.9\, Q_{max} t_{max}/E_{tot}}$$
$$r = (1 - 1/n)^{1-n}$$
$$k = rQ_{max} / E_{tot}$$

Data from:
Ingason, H. Design fire curves for tunnels. *Fire Saf. J.* **44**, 259–265 (2009).

Characterizing Conservatism

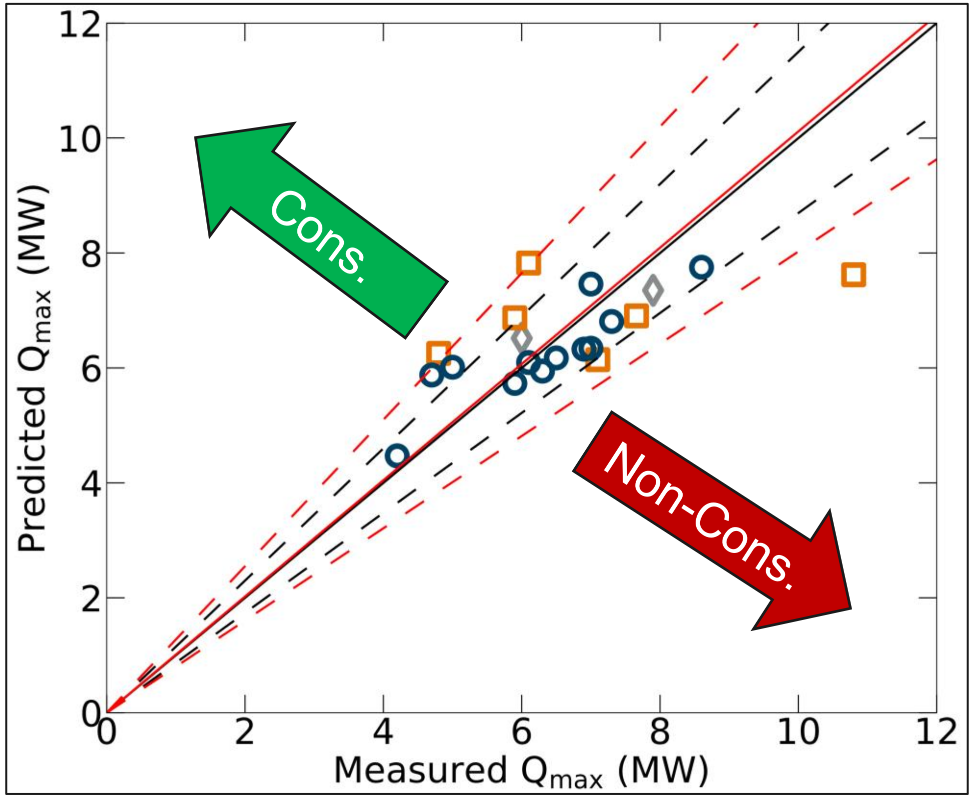
- Experimental uncertainty (σ_E): 7.5%

- Bias (δ): Systematic tendency to over-predict (>1) or under-predict (<1) the measured values.

$$\delta = \exp\left(\overline{\ln(M/E)} + 0.5\,\sigma_M^2 + 0.5\,\sigma_E^2 \right)$$

- Model error (σ_m): Scatter of error in predicted value after correcting for systematic bias.

$$\sigma_M^2 = \max[Var(\ln(M/E)) - \sigma_E^2, \sigma_E^2]$$



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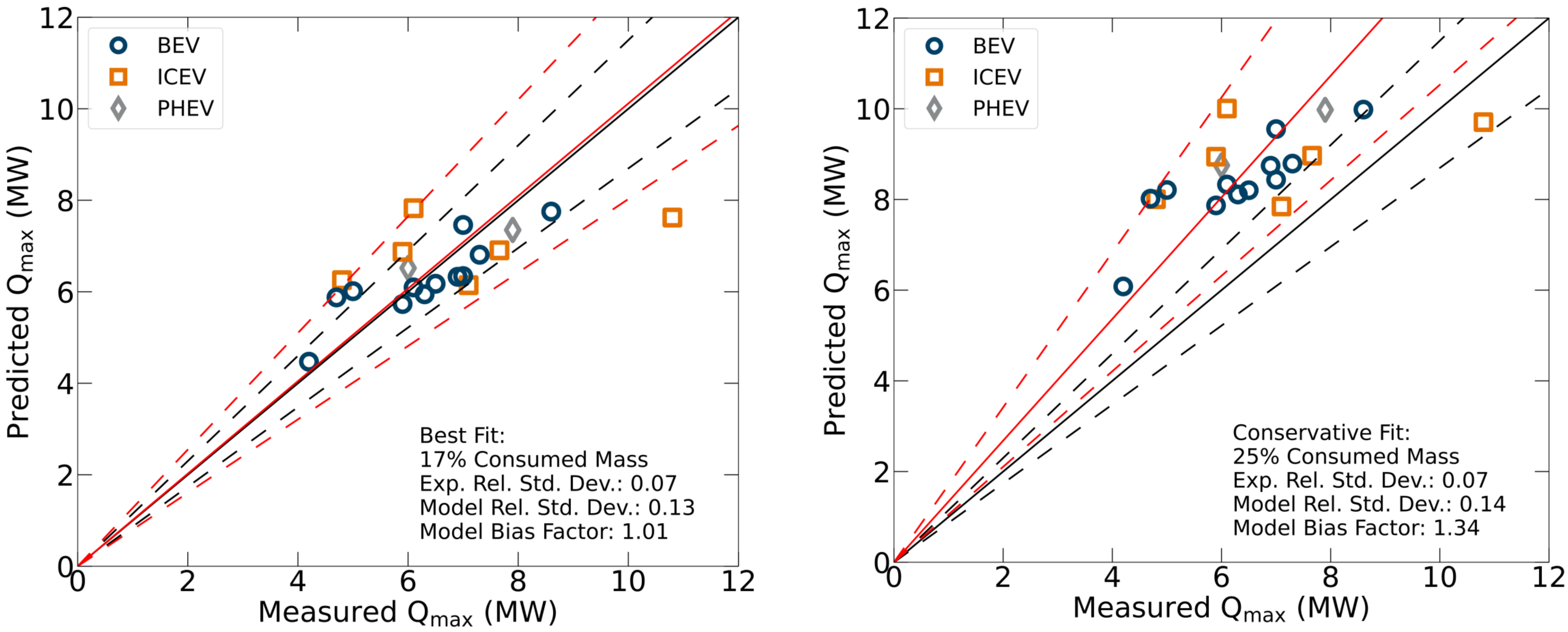
Conservative Bias in Modeling for PBD: HRR



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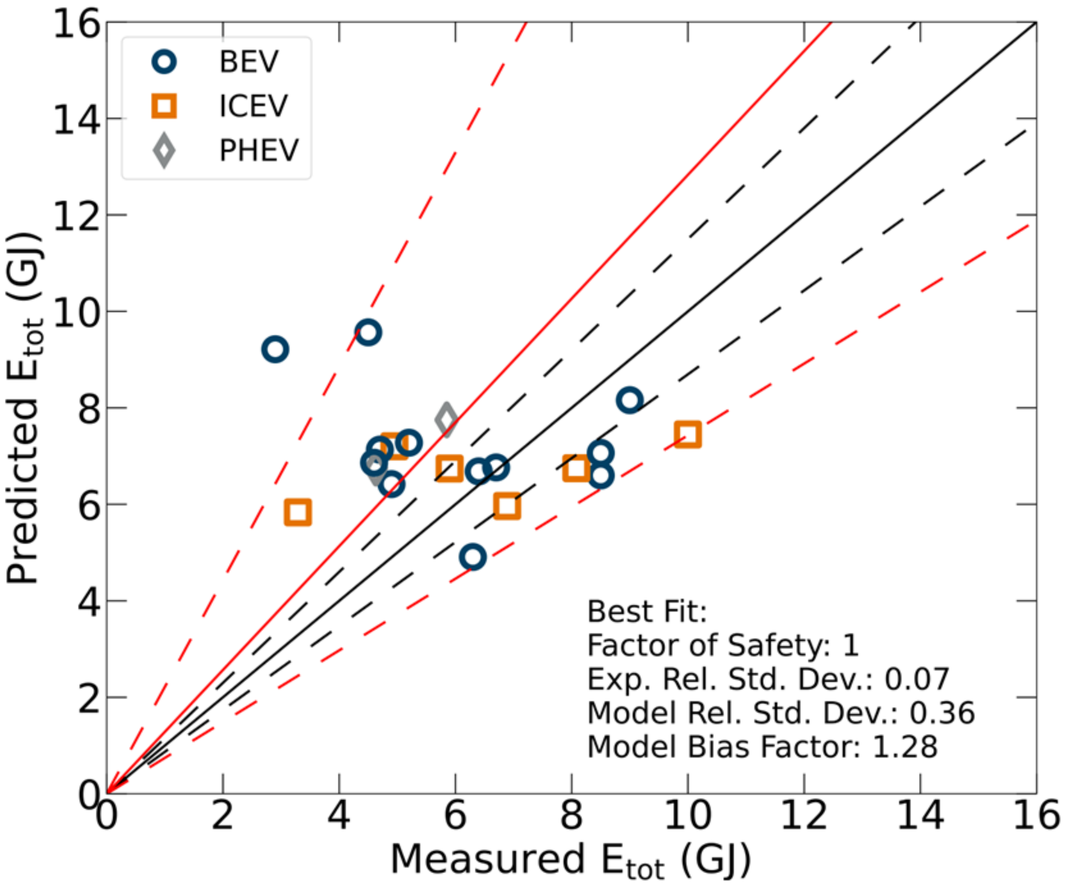
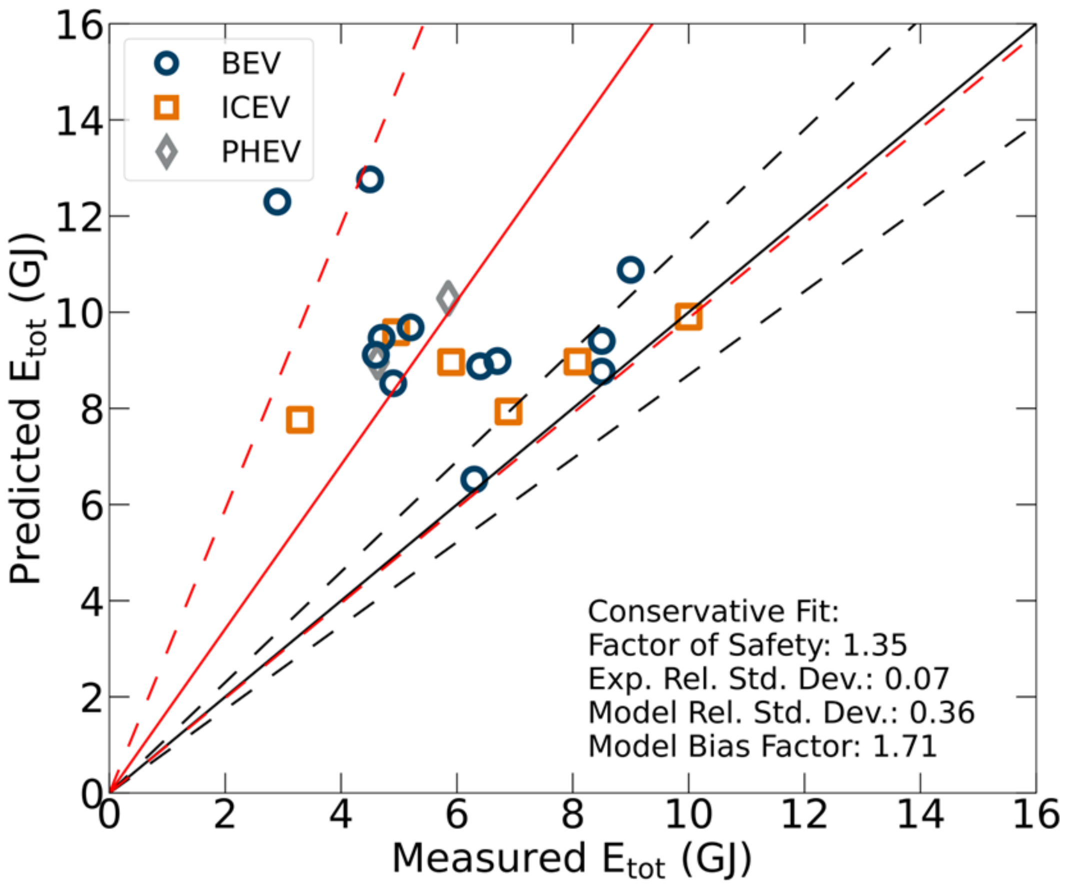
Conservative Bias in Modeling for PBD: E_{tot}





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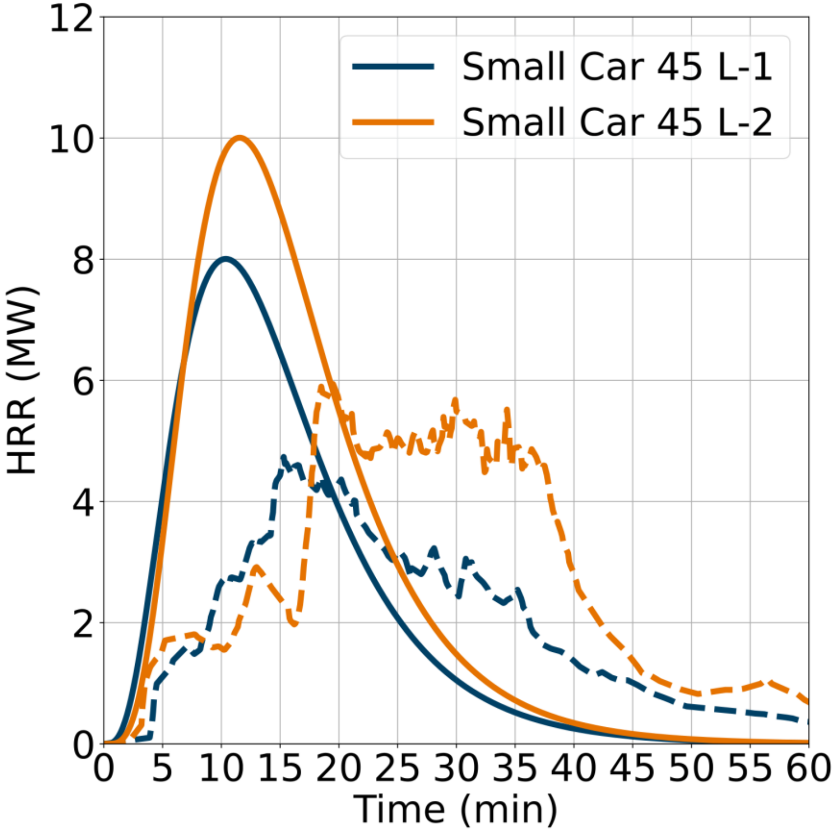
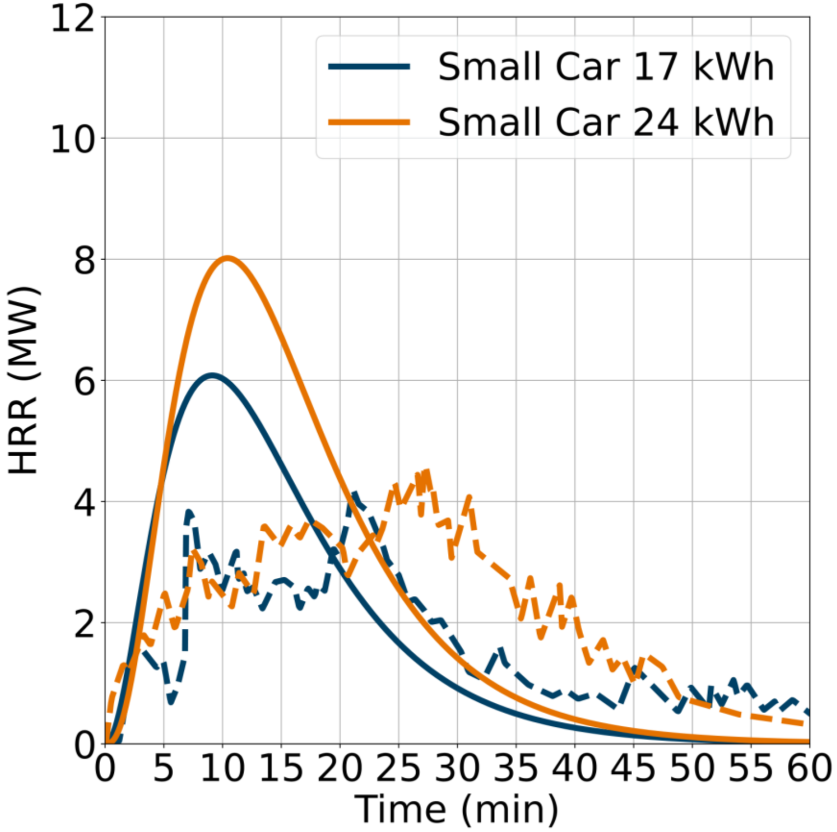
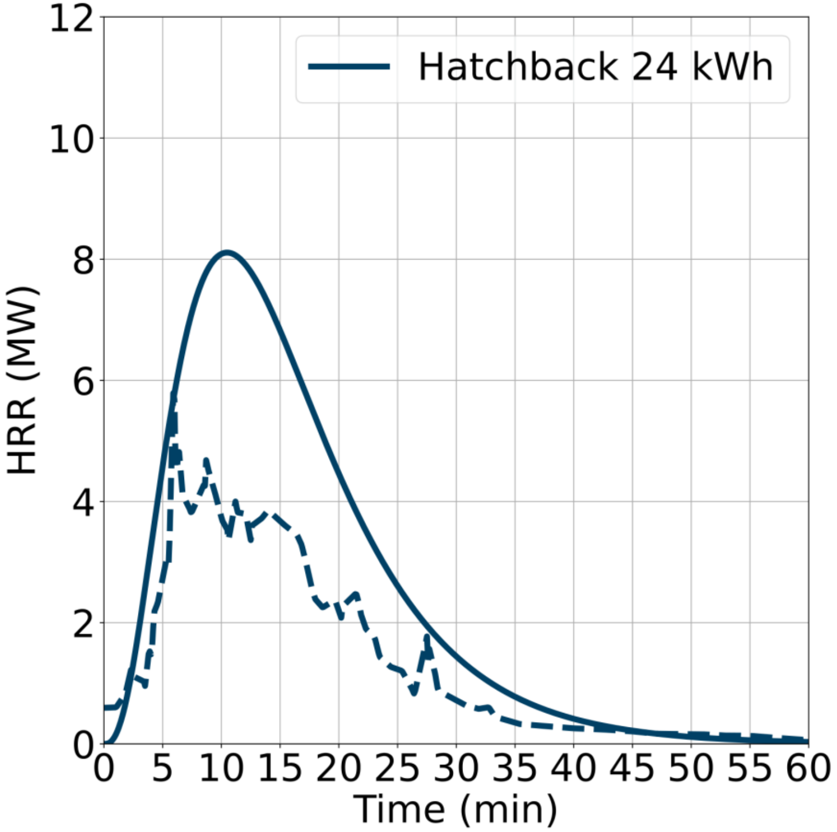
Design Fire Comparison with Experiments



Lecocq et al. ICEVs



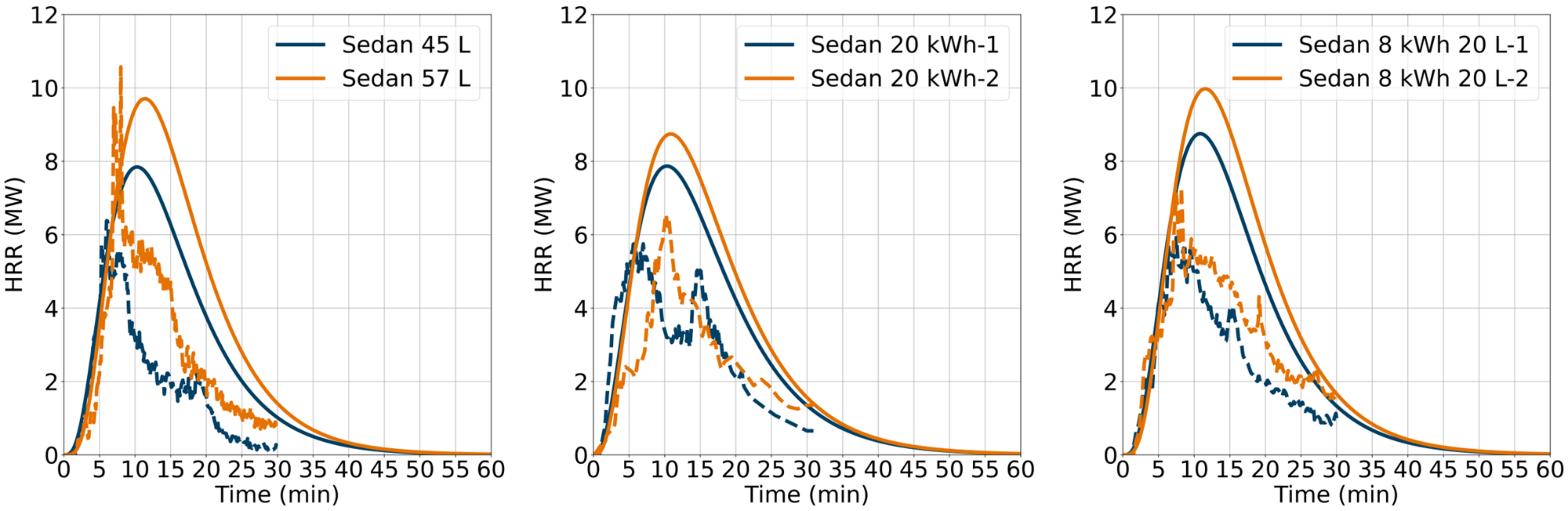
Lecocq et al. BEVs



Watanabe et al

*Hodges, J. L., Salvi, U. & Kapahi, A. Design fire scenarios for hazard assessment of modern battery electric and internal combustion engine passenger vehicles. *Fire Safety Journal.* **146**, (2024).

Design Fire Comparison with Experiments



Lam et al. ICEVs

Lam et al. BEVs

Lam et al. PHEVs

*Hodges, J. L., Salvi, U. & Kapahi, A. Design fire scenarios for hazard assessment of modern battery electric and internal combustion engine passenger vehicles. *Fire Safety Journal.* **146**, (2024).

Representative Vehicles

	BEVs		ICEVs	
Class	**Curb Weight (kg)**	**Battery Energy Capacity (kWh)**	**Curb Weight (kg)**	**Gas Tank (L)**
Compart Car	1,600	40	1,300	34
Sports Car	2,450	150	1,800	61
Large Car	2,600	115	1,760	57
8 Passenger Van	3,000	100	2,500	68
Pickup Truck	3,250	135	2,600	87
Large SUV	4,300	250	2,900	121

*Developed based on extended range vehicles in the US market, either current or announced.

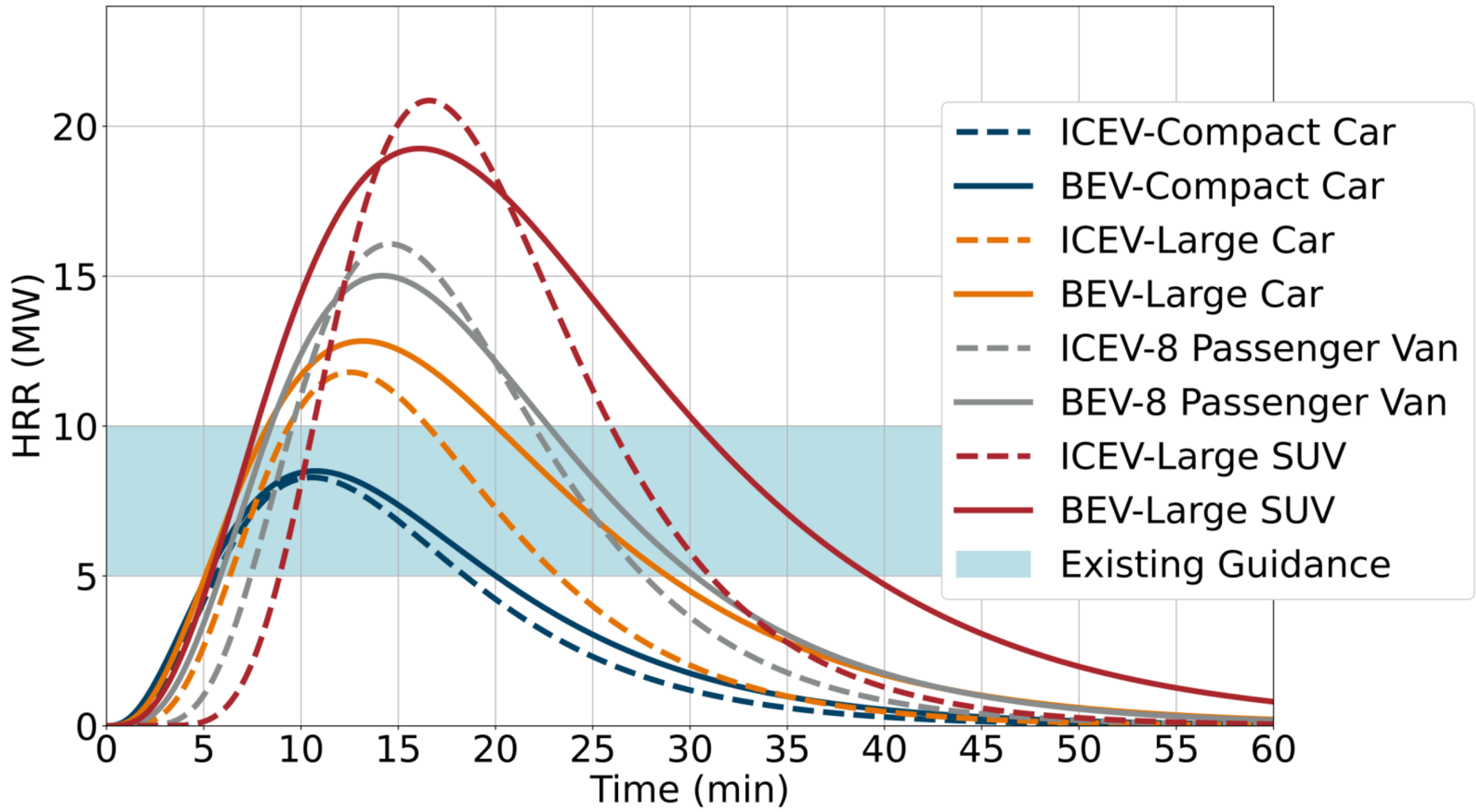
*Hodges, J. L., Salvi, U. & Kapahi, A. Design fire scenarios for hazard assessment of modern battery electric and internal combustion engine passenger vehicles. *Fire Safety Journal.* **146**, (2024).

Comparison by Propulsion Type

+ No significant difference between propulsion types

+ Conservative designs for most vehicles exceeds existing design guidance

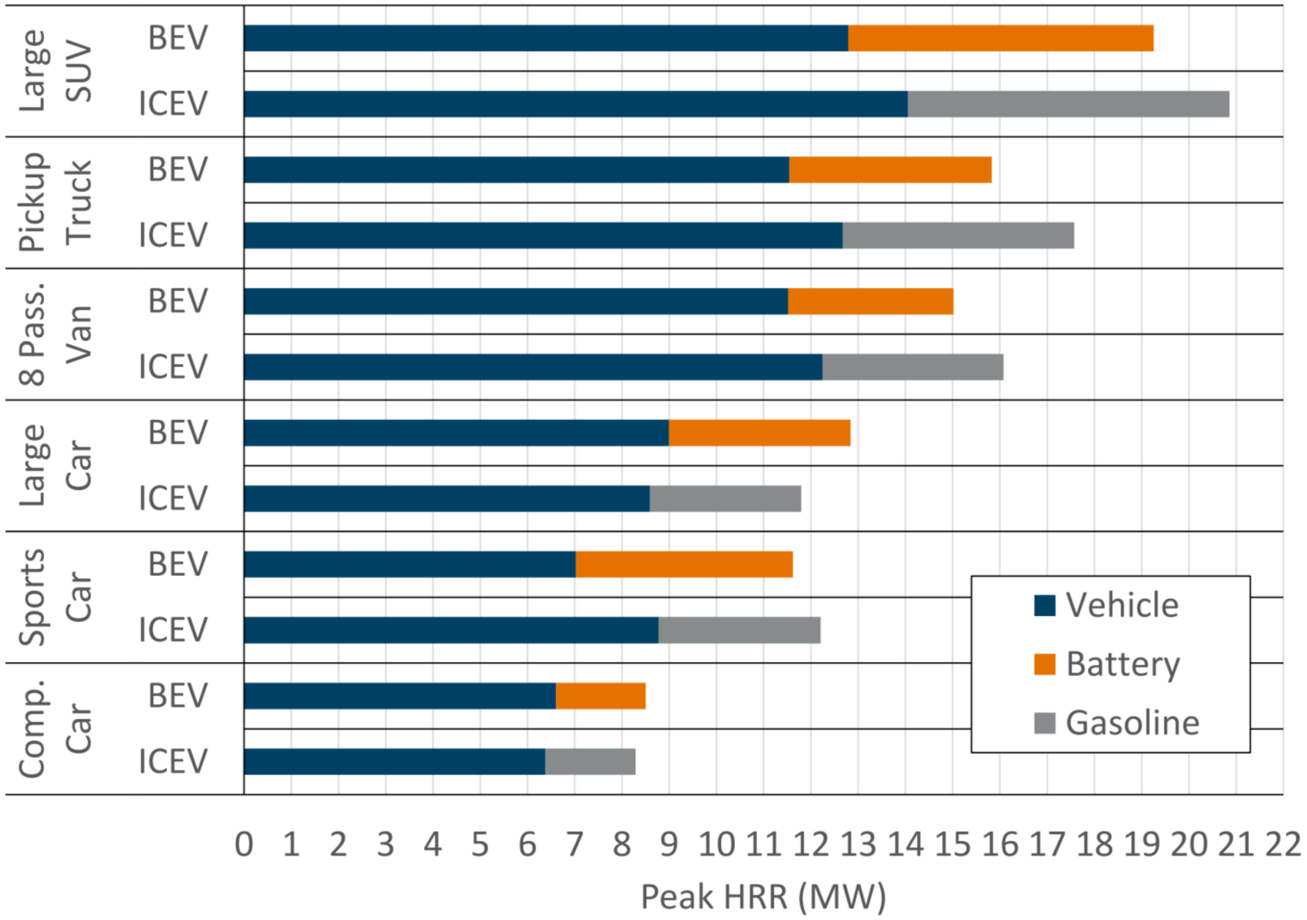
+ Vans and large SUVs exceed design guidance for multiple vehicles



*Hodges, J. L., Salvi, U. & Kapahi, A. Design fire scenarios for hazard assessment of modern battery electric and internal combustion engine passenger vehicles. *Fire Safety Journal.* **146**, (2024).

Comparison by Propulsion Type

- Propulsion system contributes similar fraction in ICEV/BEV
- Largest contribution to peak HRR are the other vehicle components
- Curb weight of BEVs higher than ICEV counterparts, but HRR is similar



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Combustion Reaction

+ Motivating example
+ Challenges
+ Analysis
  - Other Vehicle Components
  - Battery
+ Impact example

+ Objective:

Parameter	Value	Units
Fuel Reactant	*	
Soot yield	*	g/gfuel
CO yield	*	g/gfuel
Heat of combustion	*	MJ/kg

Motivating Example

- Assume a soot yield of 0.1 g/g measured with a fuel heat of combustion, $\Delta H_{c,fuel}$, of 25 MJ/kg, HRR of 5 MW, and a total heat release of 10,000 MJ within a 10 x 10 x 2.4 m room.
- Simplified approaches to modeling the combustion reaction:

Option 1: Specify propane as a surrogate fuel and use experiment heat of combustion

Fuel	C_3H_8	-
$\Delta H_{c,fuel}$	28	MJ/kg
$\Delta H_{c,O_2}$	7.4	MJ/kg
Time before O_2 consumed	99.7	s
Mass of soot produced	35.7	kg

Option 2: Specify propane as a surrogate fuel and change heat of combustion to match propane

Fuel	C_3H_8	-
$\Delta H_{c,fuel}$	44	MJ/kg
$\Delta H_{c,O_2}$	13.1	MJ/kg
Time before O_2 consumed	176.4	s
Mass of soot produced	22.7	kg

Option 3: Calculate fuel molecule with same heat of combustion as experiment with $\Delta H_{c,O_2}$ of 13.1 MJ/kg

Fuel	$C_3H_8O_1$	-
$\Delta H_{c,fuel}$	28	MJ/kg
$\Delta H_{c,O_2}$	13.1	MJ/kg
Time before O_2 consumed	176.4	s
Mass of soot produced	35.7	kg

Challenges

- Combustion reaction includes more products than just CO and Soot – Not all are measured

$$C_xH_yO_zN_v + \nu_{O_2} \rightarrow \nu_{CO_2}CO_2 + \nu_{H_2O}H_2O + \nu_{CO}CO + \nu_s Soot + \nu_{HCN}HCN + \nu_{N_2}N_2 + \text{Heat}$$

Green line	Measured, often used
Yellow line	Measured, rarely used
Red line	Not measured (typ.)

- Heterogeneous reactants
  - Passenger vehicles contain a wide range of polymers
  - Batteries contain a range of reactants (electrolyte, separator, off-gas mixture)

- Disconnect between observed ΔH_c and yields at full-scale and at component level

Analysis – Vehicle Components (Non-Propulsion)

Material	Mass (%)	$\Delta H_{c,\mathrm{fuel}}$ (MJ/kg)	CO (g/g)	CO_2 (g/g)	Soot (g/g)	H2O (g/g)
Polypropylene	7.5%	43.4	0.024	2.88	0.059	1.28
Polyurethane	1.6%	25.0	0.038	2.04*	0.125	0.83
Polyamide (Nylon)	1.4%	30.8	0.038	2.17	0.075	0.88
Polyethylene	1.2%	43.6	0.024	2.88	0.060	1.28
Acrylonitrile Butadiene Styrene	0.8%	35.4	0.059	2.75*	0.106	0.72
Polybutylene terephthalate	0.3%	23.7	0.045	2.19*	0.062	0.49
Polyethylene terephthalate	0.3%	19.5	0.030	2.04*	0.048	0.37
Other PL	3.9%	-	-	-	-	-
Rubber	6.0%	31.0	0.021	2.38*	0.078	1.06
Textiles	1.0%	23.5	0.010	2.34*	0.043	0.37
Steel	54.0%	-	-	-	-	-
Aluminum	3.0%	-	-	-	-	-
Magnesium	1.0%	-	-	-	-	-
Other	18.0%	-		-	-	-
Weighted average by combustible mass ($CH_{1.7}O_{0.09}N_{0.01}$)		35.4	0.026	2.56	0.072	0.89

[1] Koromila 2023

[2] FSRI material database

[3] NIST fire calorimetry database

Calculated from stoichiometry with $\Delta H_{c,O2}$ = 13.1 MJ/kg

*Significant difference from stoichiometry and reported values in SFPE handbook

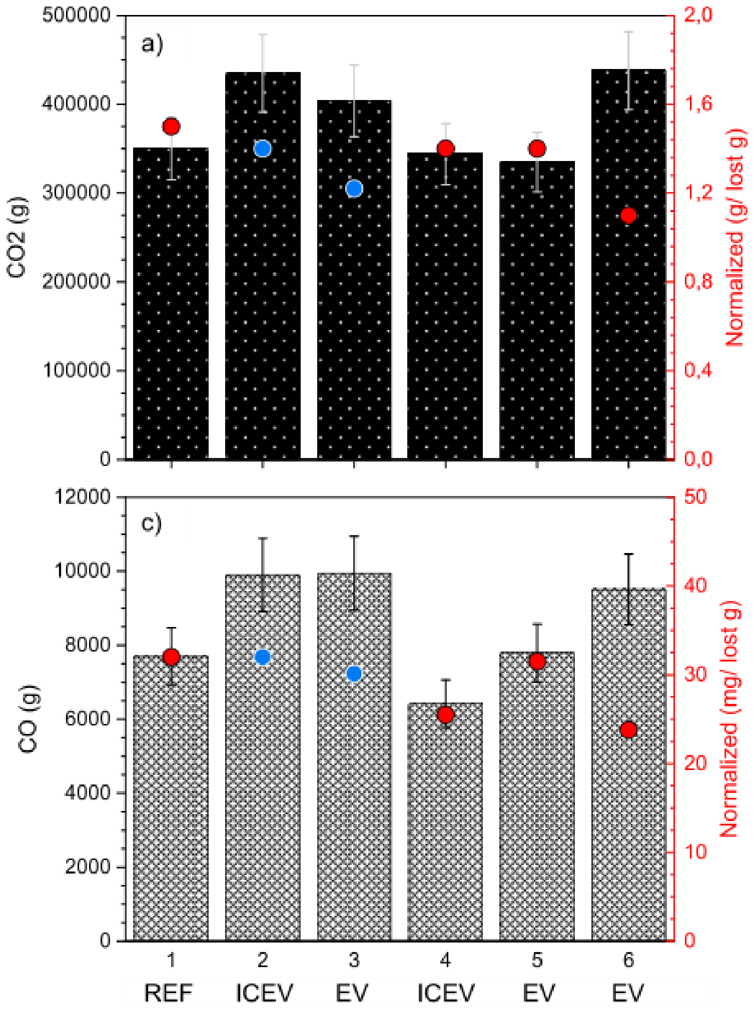
[1] I.A. Koromila, K.J. Spyrou, Design Fire Methodology for Vehicle Spaces Onboard Ships, Fire Technol 59 (2023) 1725–1759. https://doi.org/10.1007/s10694-023-01403-w.
[2] https://materials.fsri.org/
[3] https://www.nist.gov/el/fcd

Analysis – Vehicle Components (Non-Propulsion)

- Disconnect between observed $\Delta H_{c,fuel}$ and yields at full-scale and at component level

Method	$\Delta H_{c,\text{fuel}}$ (MJ/kg)	CO (g/g)	CO_2 (g/g)	Soot (g/g)	H2O (g/g)
Component calculation	35.4	0.026	2.56	0.072	0.89
Full-scale measurement[1]	19.8	0.029	1.32	-	-

- Possible reasons
  - Systematic bias in measurements (mass, species)
  - Portion of mass loss in full-scale testing not from combustibles (e.g., broken glass, melted aluminum, metal ejecta, etc.)



[1] J. Hynynen, O. Willstrand, P. Blomqvist, P. Andersson, Analysis of combustion gases from large-scale electric vehicle fire tests, Fire Safety Journal 139 (2023) 103829. https://doi.org/10.1016/j.firesaf.2023.103829.

Analysis – Vehicle Components (Non-Propulsion)

- Equivalent species yields
  - Calculate total species produced by a fire under both conditions (i.e., $\Delta H_{c,fuel}$ and yields) at same heat release rate
  - Re-calculate yield based on full-scale $\Delta H_{c,fuel}$

Method	$\Delta H_{c,\text{fuel}}$ (MJ/kg)	CO (g/g)	CO_2 (g/g)	Soot (g/g)	H_2O (g/g)
Component calculation	35.4	0.026	2.56	0.072	0.89
Component equivalent yields	19.8	0.015	1.43	0.040	0.50
Full-scale measurement[1]	19.8	0.029	1.32	0.040	1.01

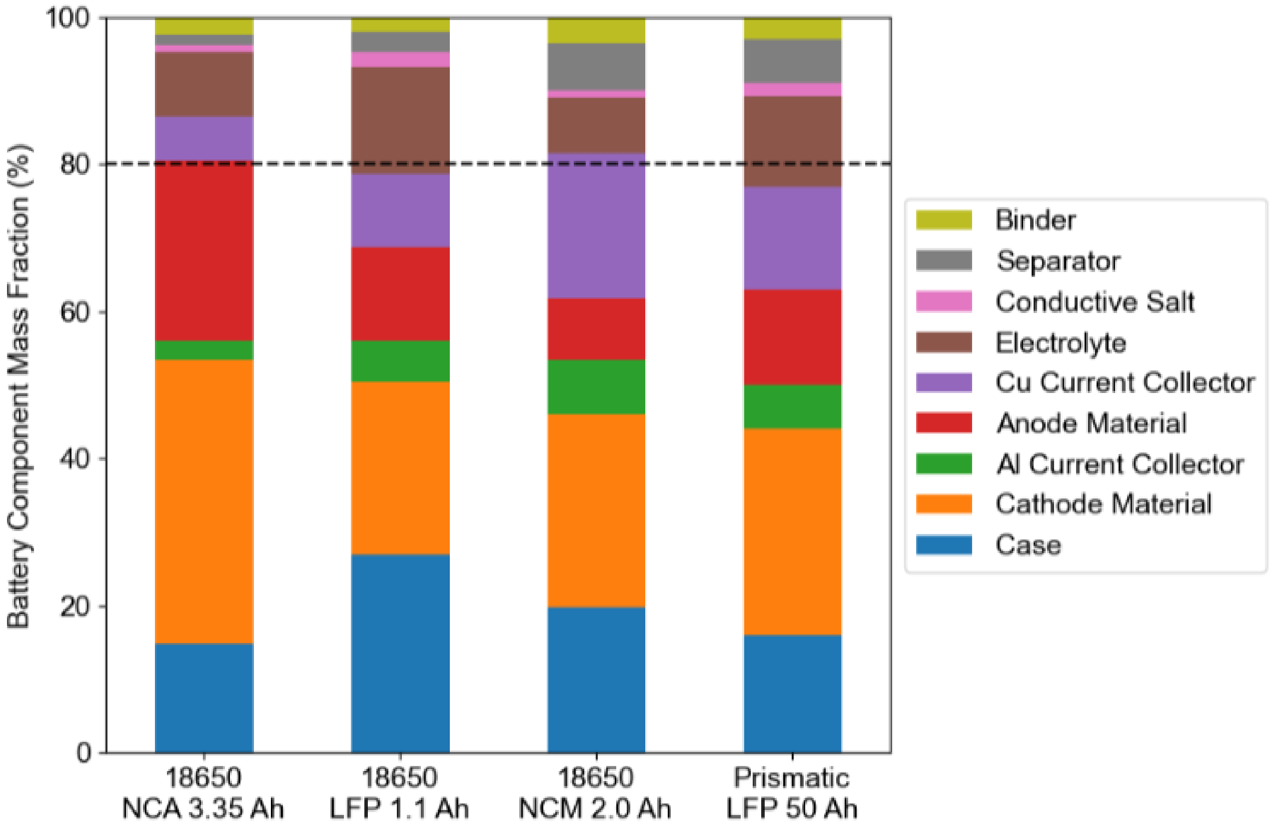
Calculated based on equivalent yield to component calculation

Calculated from stoichiometry with $\Delta H_{c,O2}$ = 13.1 MJ/kg, y_s from equivalent yield calculation, and assuming only H, C, and O in fuel molecule and HCN yield is zero.

- Representative combustion reaction
  - Take higher of each yield as representative (i.e., CO and H_2O)
    - Note whether higher H2O yield is conservative or not will depend on the objective of the scenario

Configuration	Fuel Molecule	$\Delta H_{c,\text{fuel}}$ (MJ/kg)	CO (g/g)	CO_2 (g/g)	Soot (g/g)	H_2O (g/g)
Hodges Cons.	$CH_{3.75}O_{1.11}$	16.0	0.023	1.16	0.033	1.01
Rise Exp.	$CH_{3.00}O_{0.75}$	19.8	0.029	1.44	0.040	1.00
Hodges Best Fit	$CH_{2.51}O_{0.49}$	24.0	0.035	1.74	0.049	1.01

Analysis – Battery Cell Composition



Component	Mass (%)	$\Delta H_{c,\text{fuel}}$ (MJ/kg)	Energy* (%)
Off-gas (H2, CO2, CO, + HC)	2-4	11.7** 65.2***	8
Liquid electrolyte (e.g., DMC)	8-14	12-24	27
Plastics (binder, separator, etc.) (e.g., PE/PP)	4-10	43.6	65

*Assumes all fuel is consumed

**Includes dilution by CO and CO_2

***Does not include dilution by CO and CO_2

Cell composition estimated from:
[1] Golubkov, A. W., et al., 2015, "Thermal Runaway of Commercial 18650 Li-Ion Batteries with LFP and NCA Cathodes – Impact of State of Charge and Overcharge," RSC Adv.
[2] Mao, B., et al., 2020, "Refined Study on Lithium Ion Battery Combustion in Open Space and a Combustion Chamber," Process Safety and Environmental Protection.
[3] Chen, S., et al., 2020, "Identification and Characteristic Analysis of Powder Ejected from a Lithium Ion Battery during Thermal Runaway at Elevated Temperatures," Journal of Hazardous Materials.

Energy contributions estimated from:
[4] S. Wang, et al., Experimental study of gas production and flame behavior induced by the thermal runaway of 280 Ah lithium iron phosphate battery, Journal of Energy Storage 74 (2023) 109368. https://doi.org/10.1016/j.est.2023.109368.

Analysis – Battery Off-Gas (Combustible Gases Only)

Gas Species	Mass* (%)	$\Delta H_{c,\mathrm{fuel}}$ (MJ/kg)	CO (g/g)	CO_2 (g/g)	Soot (g/g)	H2O (g/g)	$\Delta H_{c,O_2}$** (MJ/kg)
Acetylene (C_2H_2)	1.3	48.2	0.042	2.96	0.096	0.69	17.3
Benzene (C_6H_6)	0.9	40.1	0.067	2.61	0.181	0.69	15.7
Butane (C_4H_{10})	1.7	45.7	0.007	2.91	0.029	1.55	13.1
Butene (C_4H_8)	8.0	45.3	0.042	2.65	0.115	1.28	14.7
Ethane (C_2H_4)	14.3	47.1	0.001	3.09	0.013	1.28	13.9
Hexane (C_6H_{14})	0.5	44.7	0.009	2.94	0.031	1.46	13.0
Hexene (C_6H_{12})	1.5	44.4	0.021	2.88	0.062	1.28	13.7
Hydrogen (H_2)	24.9	120.0	0.000	0.00	0.000	8.94	15.1
Methane (CH_4)	24.5	50.0	0.000	2.74	0.000	2.25	12.5
Pentane (C_5H_{12})	2.4	45.0	0.006	2.96	0.022	1.50	12.9
Pentene (C_5H_{10})	2.4	44.6	0.024	2.84	0.07	1.28	13.9
Propane (C_3H_8)	3.8	46.4	0.005	2.90	0.024	1.63	13.0
Propylene (C_3H_6)	9.9	45.8	0.017	2.76	0.095	1.28	14.5
Toluene (C_7H_8)	3.9	39.7	0.064	2.61	0.173	0.78	15.1
Weighted average by combustible mass ($CH_{7.4}$)		65.2	0.010	2.12	0.035	3.42	14.2

Calculated from stoichiometry with fuel molecule, CO, and soot yield

*Does not include N_2 (44.8%, inerting gas), CO_2 (17.5%), or CO (4.3%) by volume.

**Significant difference from reported values in SFPE handbook which do not account for soot and CO yields

Composition from pressure vessel testing for 3.2 V 280 Ah prismatic $LiFePO_4$ cell at 100% state of charge in the Jensen Hughes laboratory. Composition will vary by make and model.

Analysis – Battery Electrolyte

Electrolyte	$\Delta H_{c,\text{fuel}}$ (MJ/kg)	CO (g/g)	CO_2 (g/g)	Soot (g/g)	H2O (g/g)	$\Delta H_{c,O_2}$ (MJ/kg)
DEC ($C_5H_{10}O_3$)	21.6	0.131	1.66	0.0000	0.76	14.0
DMC ($C_3H_6O_3$)	14.6	0.123	1.27	0.0000	0.60	14.6
EMC ($C_4H_8O_3$)	18.4	0.129	1.49	0.0000	0.69	14.1
EC ($C_3H_4O_3$)	12.4	0.074	1.38	0.0000	0.41	14.3
PC ($C_4H_6O_3$)	16.6	0.117	1.54	0.0000	0.53	14.0
EA ($C_4H_8O_2$)	23.8	0.154	1.74	0.0040	0.82	13.8
EC–DMC (0.5/0.5)	13.5	0.029	1.44	0.0000	0.51	13.9
EC–DEC (0.57/0.43)	16.4	0.049	1.61	0.0000	0.59	13.2
EC–DEC (0.37/0.63)	18.2	0.113	1.57	0.0016	0.65	13.6
EC–EMC (0.54/0.46)	15.2	0.057	1.50	0.0005	0.55	13.6
EC–EMC (0.34/0.66)	16.4	0.111	1.46	0.0000	0.61	13.9
EC–DEC–DMC (0.37/0.27/0.37)	15.8	0.096	1.45	0.0004	0.59	13.9
EC–PC–DMC (0.19/0.16/0.56)	13.2	0.043	1.46	0.0001	0.55	12.6
EC–DMC–EA (0.34/0.33/0.34)	17.1	0.025	1.61	0.0015	0.61	13.7
Average of mixtures ($C_{3.5}H_{6.2}O_{2.9}$)	15.7	0.065	1.51	0.0005	0.58	13.5

Calculated from stoichiometry with fuel molecule, CO, and soot yield

G.G. Eshetu, S. Grugeon, S. Laruelle, S. Boyanov, A. Lecocq, J.-P. Bertrand, G. Marlair, In-depth safety-focused analysis of solvents used in electrolytes for large scale lithium ion batteries, Phys. Chem. Chem. Phys. 15 (2013) 9145. https://doi.org/10.1039/c3cp51315g.

Analysis – Battery Cell Combustion Reaction

Combustible component	Mass (%)	Energy (%)	$\Delta H_{c,\text{fuel}}$ (MJ/kg)	CO (g/g)	CO_2 (g/g)	Soot (g/g)	H2O (g/g)	$\Delta H_{c,O_2}$* (MJ/kg)
Off-gas ($CH_{7.4}$)	3.7	8	65.2	0.010	2.12	0.0350	3.42	14.2
Liquid electrolyte ($C_{3.5}H_{6.2}O_{2.9}$)	51.6	27	15.7	0.065	1.52	0.0005	0.59	13.3
Plastics (C_2H_4)	44.7	65	43.6	0.024	2.88	0.0600	1.28	13.4
Weighted average ($CH_{2.1}O_{0.3}$)			30.0	0.045	2.15	0.0284	1.00	13.5

* Scaled based on consumed oxygen fraction

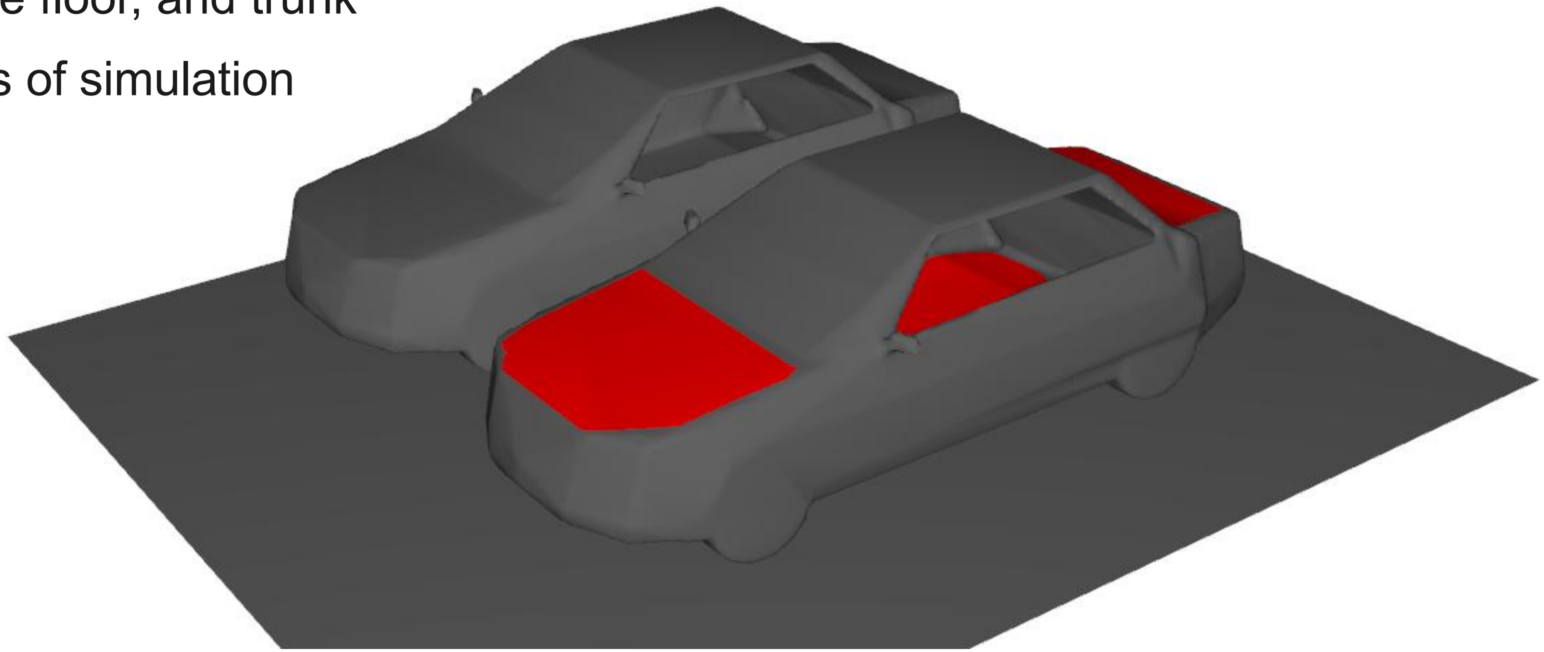
Note 1: These soot yields are calculations based on the combustion reaction generating carbon particulates. Other particulates (e.g., metals) may also be generated which could impact tenability and heat transfer analyses.

Note 2: These CO and CO_2 yields neglect the CO and CO_2 which is released as part of the off-gas. These components should be injected in the computational domain as part of the boundary condition where the fuel mixture is injected.

Case Example

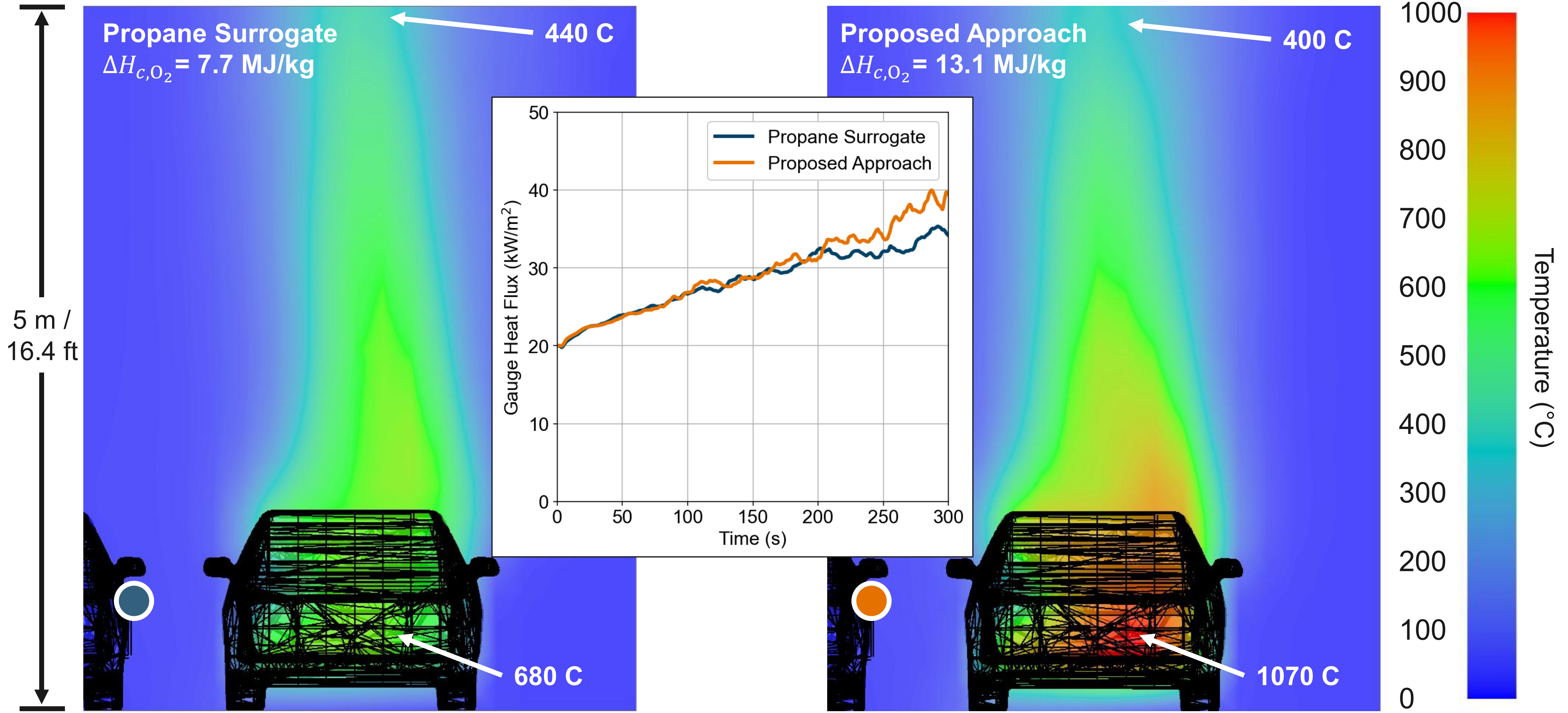
- Two adjacent sedans modeled in Fire Dynamics Simulator (FDS), separated by 0.75 m (30 in.)
- Windows open in both vehicles
- HRR distributed between hood, inside floor, and trunk
- Steady HRR at peak for 300 seconds of simulation
- Prescribed radiative fraction of 0.35

Parameter	Value	Unit
Vehicle	BEV Sedan	
Curb Weight	1,600	Kg
Battery Energy Capacity	40	kWh
Liquid Fuel Tank Size	0	L
Peak HRR	6.4	MW
Total Energy	7.3	GJ
$\Delta H_{c,\mathrm{fuel}}$	25.59	MJ/kg
Fuel	$CH_{2.41}O_{0.43}$	
yCO	0.038	g/g
ySoot	0.043	g/g
$\Delta H_{c,O_2}$	13.1	MJ/kg



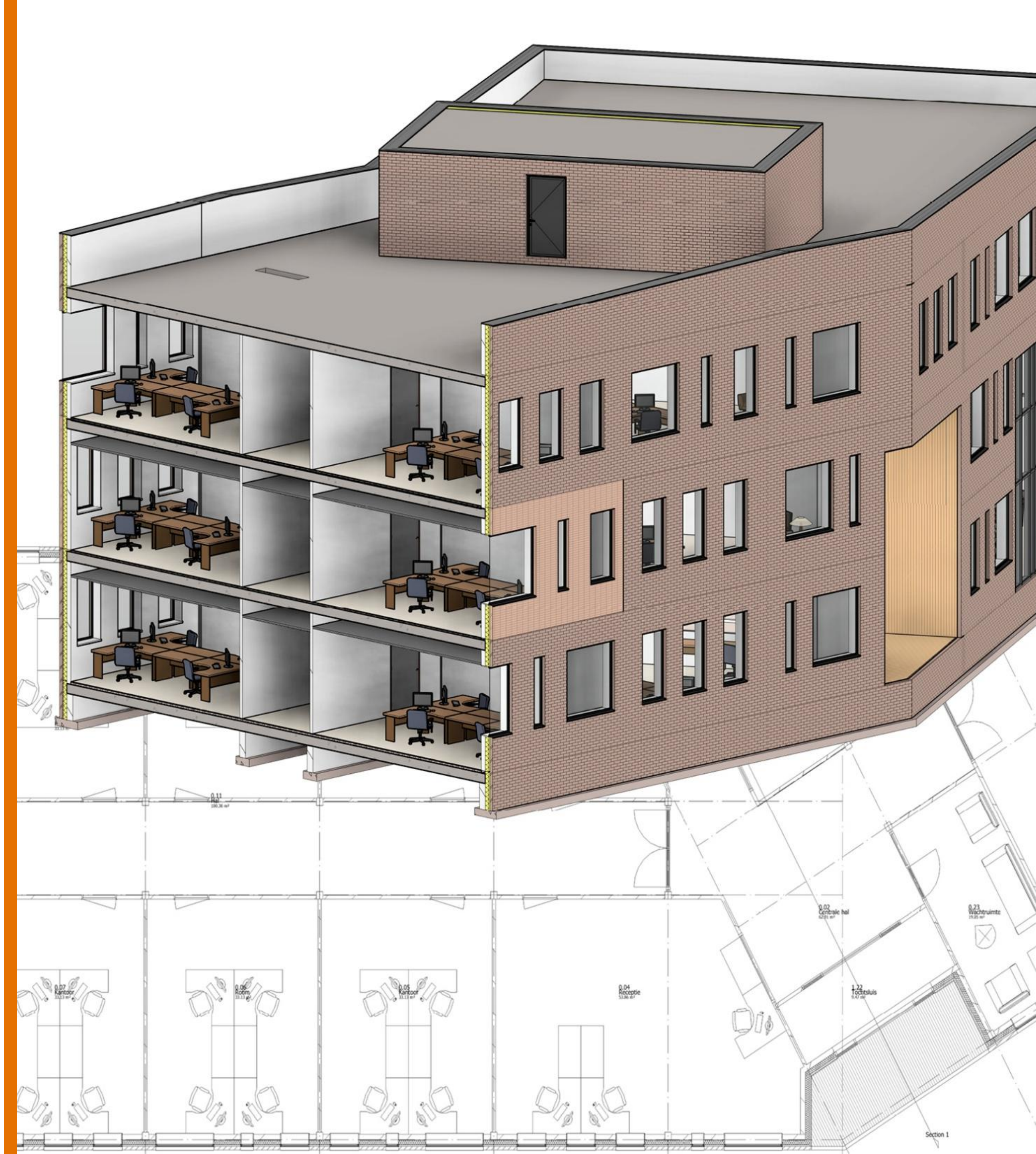
- One model uses propane with modified heat of combustion and yields (results in $\Delta H_{c,O_2}$= 7.3 MJ/kg)
- One model uses presented combustion reaction approach

Impact on Heat Transfer



Performance Base Design: Additional Considerations

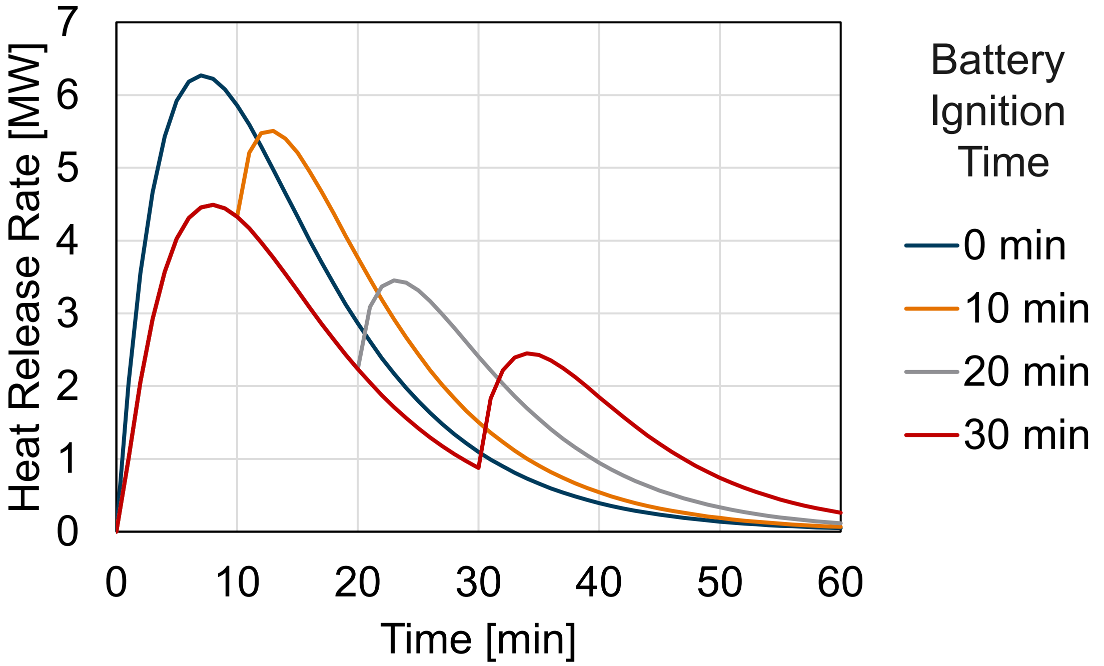
+ Delayed Ignition of Fuels
+ Larger vehicles
+ Mitigation

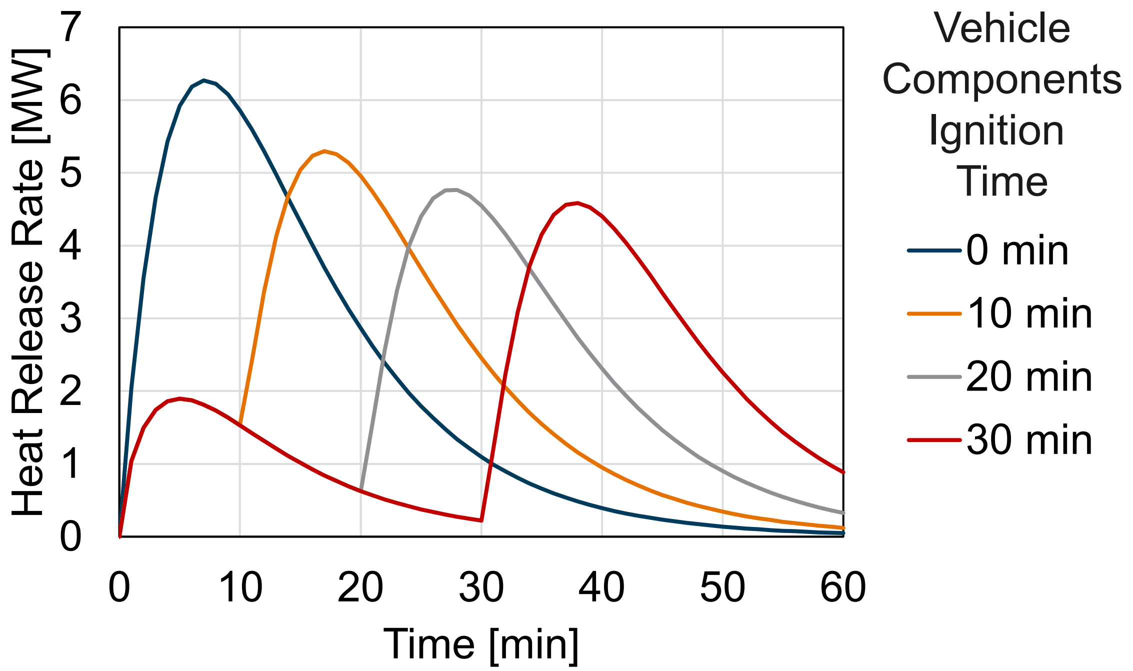


Delayed Ignition of Fuels

- Assumptions in presented model
  - All components ignite from start and grow at fixed growth rate
  - Fire does not spread to adjacent vehicles
- Not always the observed behavior in practice
- Model can be adapted to delay ignition of components to see impact

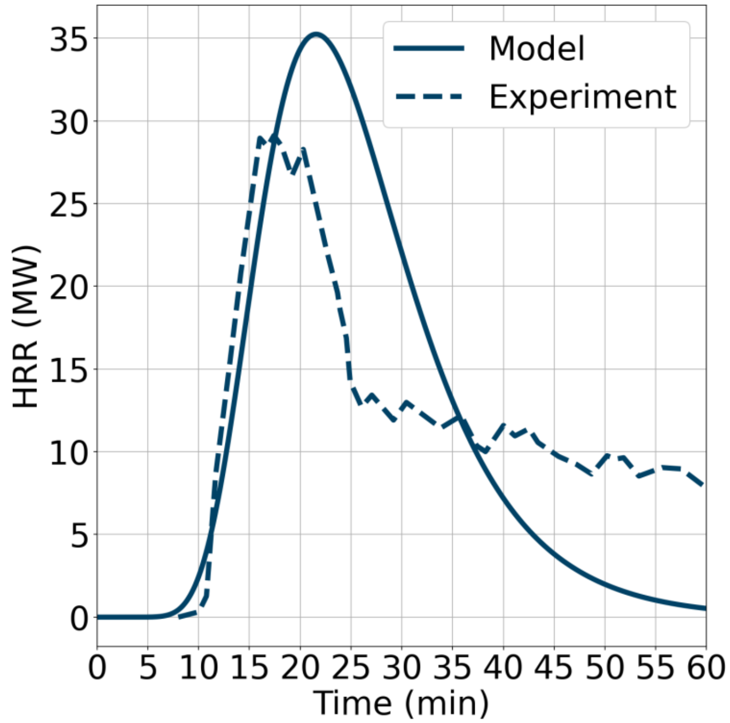
Parameter	Value	Unit
Vehicle	BEV Sedan	
Curb Weight	1,600	Kg
Battery Energy Capacity	40	kWh
Liquid Fuel Tank Size	0	L
Peak HRR	6.4	MW
Total Energy	7.3	GJ

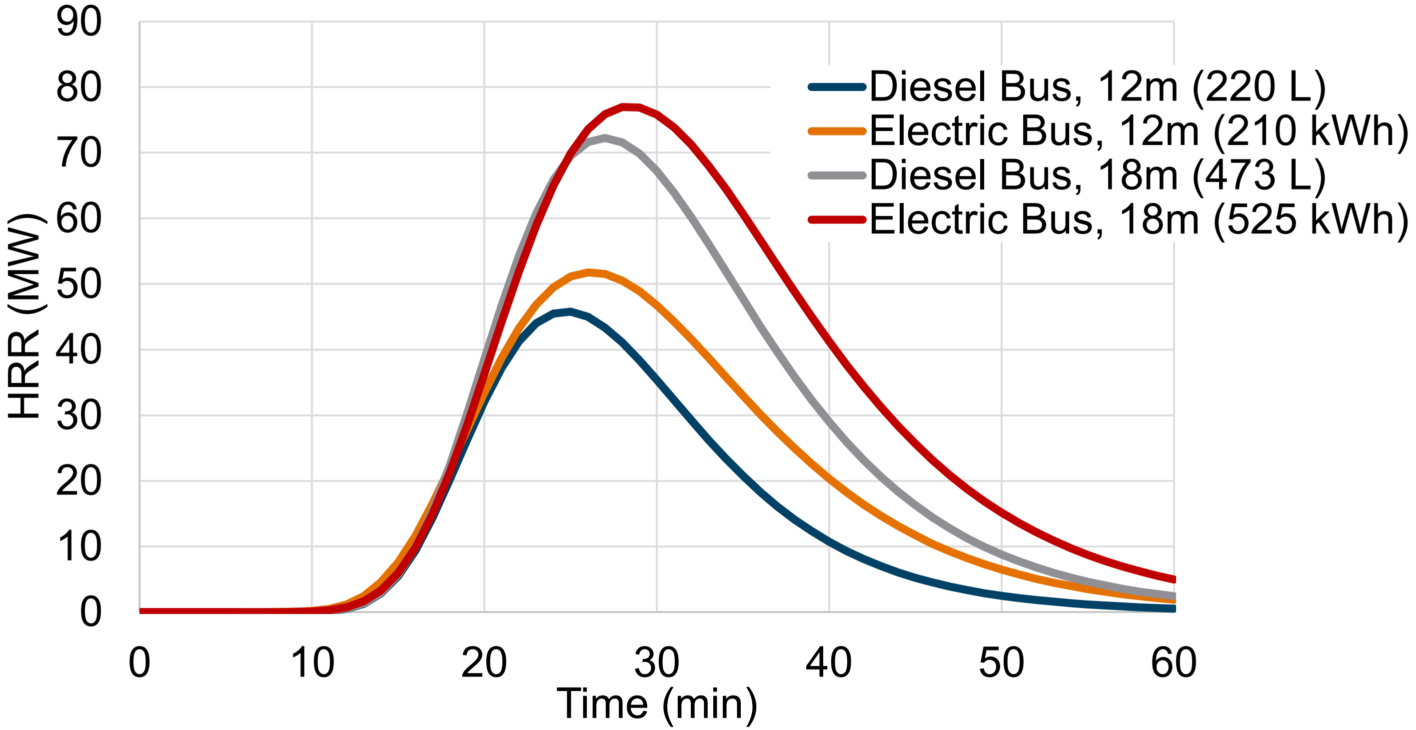




Larger Vehicles – Example Extrapolation to Buses

Parameter	EUREKA Bus	12 m Bus		18 m Bus		Unit
Vehicle	40 Seat ICE Bus	ICE	BEV	ICE	BEV	
Curb Weight	10,000	10,000	15,000	17,690	23,200	Kg
Battery Energy Capacity	0	0	210	0	525	kWh
Liquid Fuel Tank Size	23	220	0	473	0	L
Peak HRR	35.2	45.8	51.8	72.3	77.1	MW
Total Energy	41.5	48.0	65.4	87.7	105.2	GJ



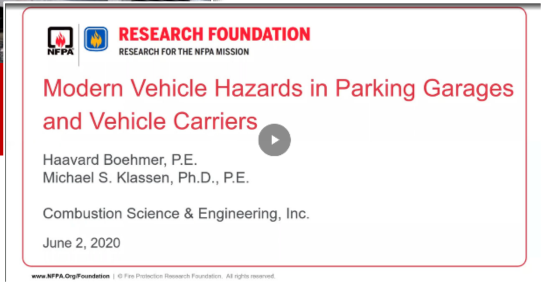


Data from: Fires in transport tunnels: report on full-scale tests ; Eureka-Project EU 499: FIRETUN, 1995.

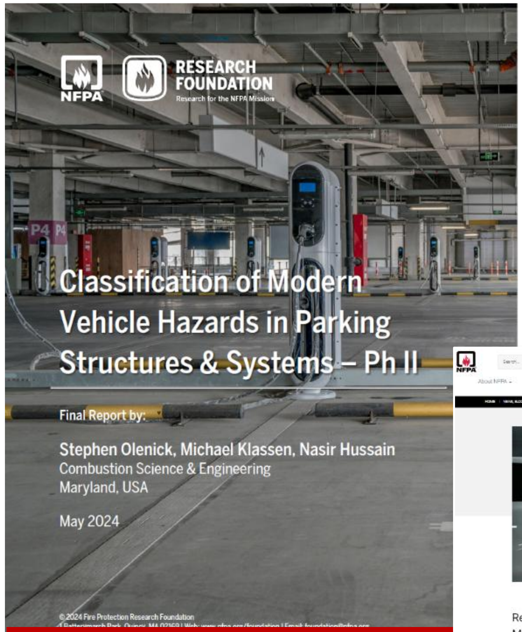
Mitigation (Credit: Fire Protection Research Foundation)

Overarching Goal: To quantify the fire hazard and spread characteristics of modern vehicles (ICEs and EVs) in parking structures to inform fire protection requirements.

Phase 1



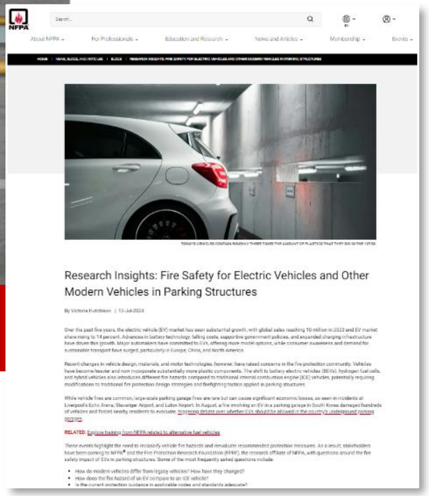
www.nfpa.org/webinars

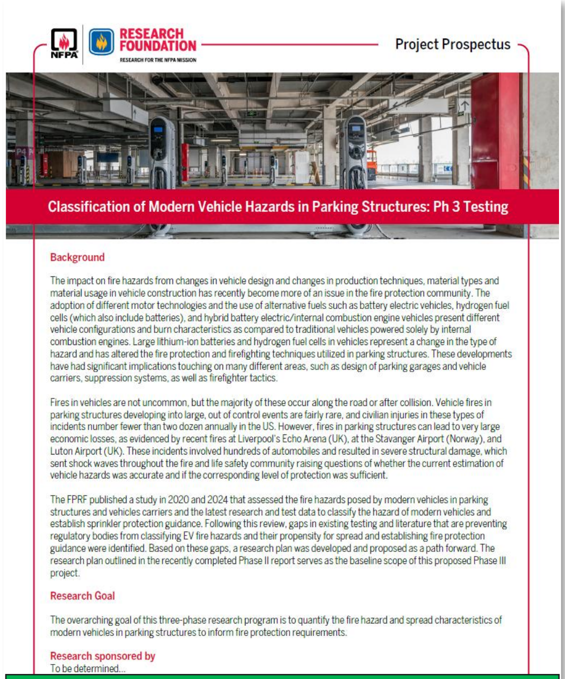


Phase 2

Resources available at: www.nfpa.org/foundation

Blogs at nfpa.org





Ph 3 (active)

2020 — 2024 — 2025

RESEARCH FOUNDATION
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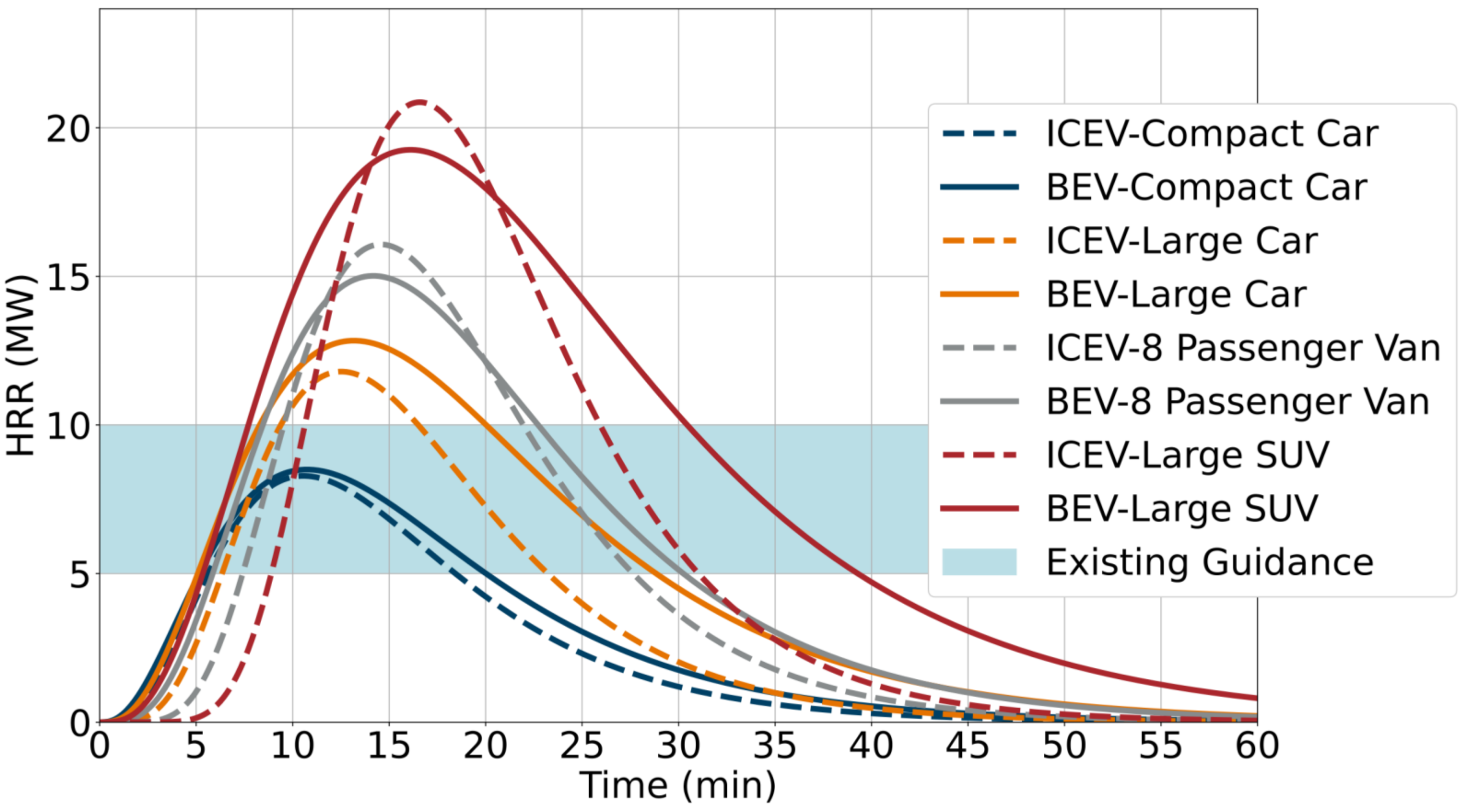
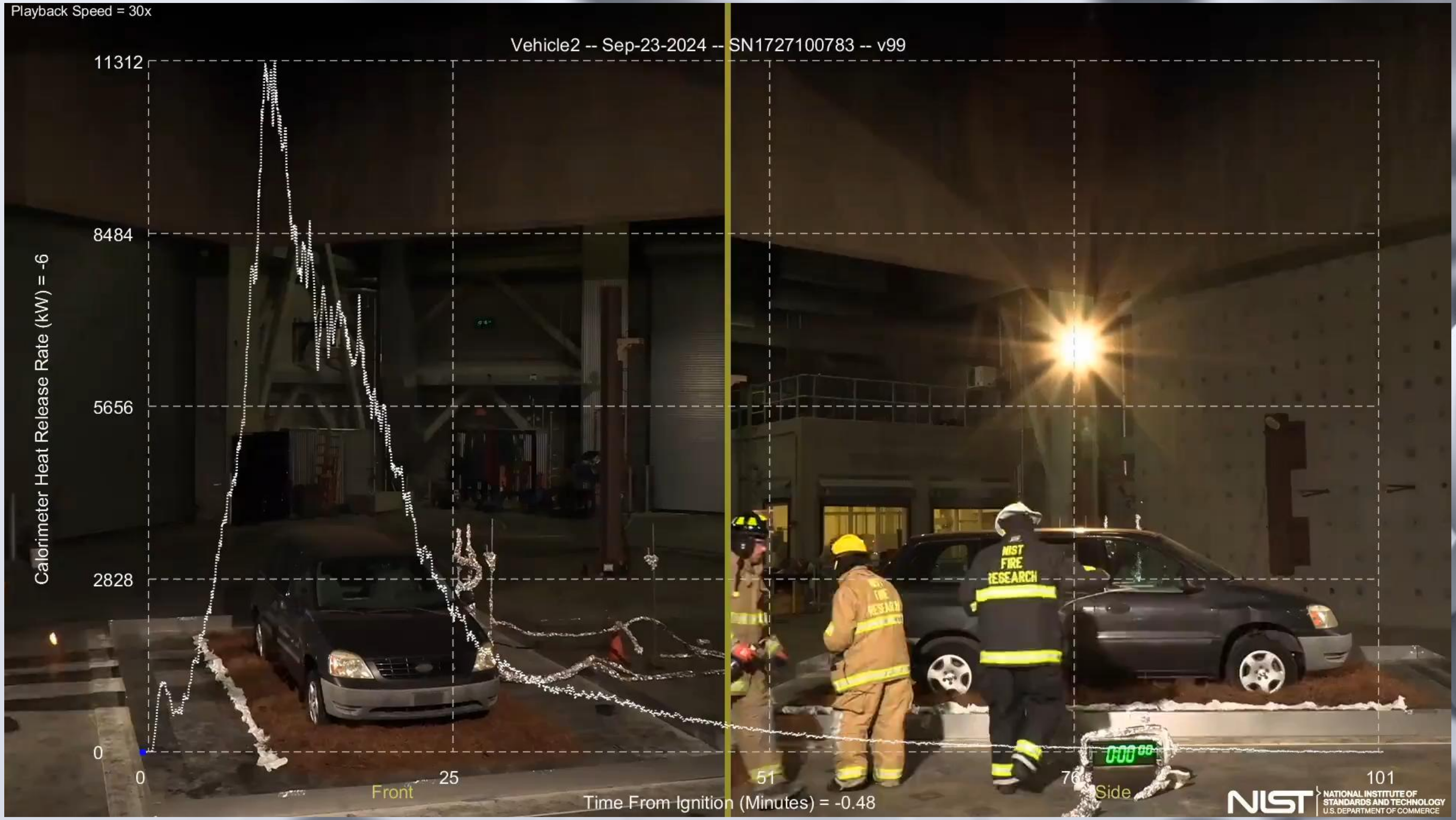
Conclusion

- Individual vans and large SUVs exceed design guidance for multiple vehicles
- Largest contribution to peak HRR are the non-propulsion (other) vehicle components
- Combustion reaction has an impact on both heat transfer and tenability predictions
- Careful consideration is needed on scaling vehicle measurements



Questions?



[1] Giovanni Di Cristina, Matthew Bundy, and Anthony Hamins, Vehicle Fires in a WUI-Type Scenario, RISE Conference Proceedings 2025
[2] NIST, “Fire Calorimetry Database (FCD)”, https://www.nist.gov/el/fcd/design-fires-vehicles-pine-straw-bed