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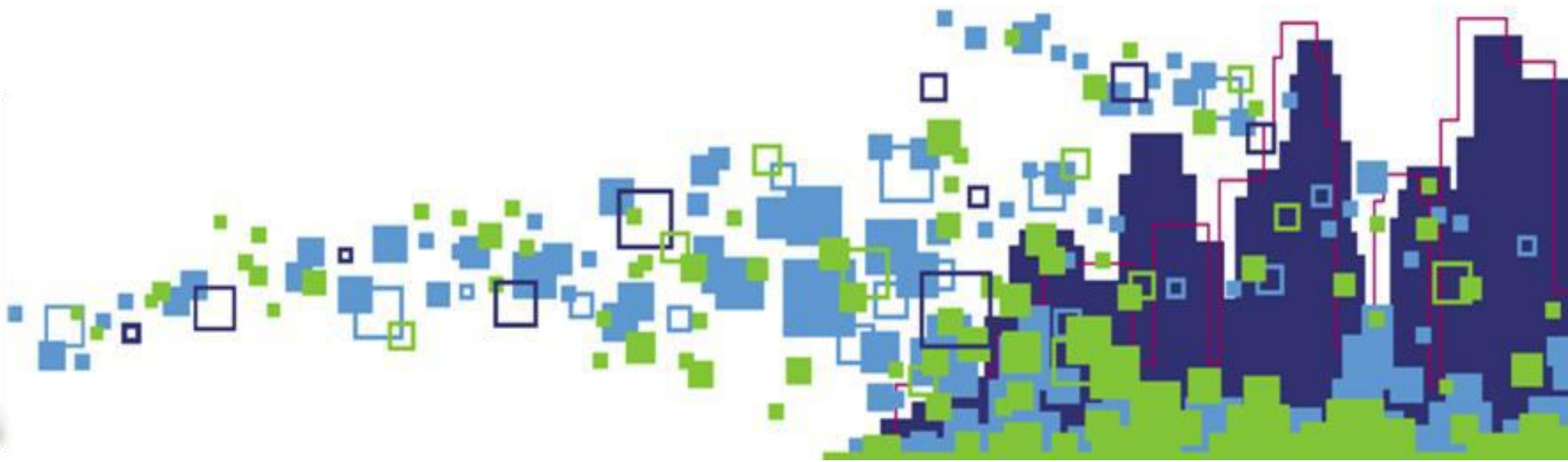
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Electrical Safety of Heavy Duty Transit Buses

EVS29 Symposium

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Electrical Safety of Heavy Duty Transit Buses

- ☐ Introduction to electric heavy duty transit buses
- ☐ Overview of electrical risks
- ☐ Basic design for safety
- ☐ How to mitigate and quantify safety risks
- ☐ Calculation example
- ☐ Conclusion





Emergence of fully electric heavy-duty transit vehicles and safety

- Diesel buses have evolved and made the technology safe and reliable
- Electric vehicles with hundreds of kWh represent an equivalent risk
- Safety standards such as SAE J2910 and ISO 6469 provide a solid framework for safe electric vehicle design but...
- Standards alone cannot guarantee complete safety
- Closing the gap is the manufacturer's responsibility



Technologies are evolving faster than regulations and standardization



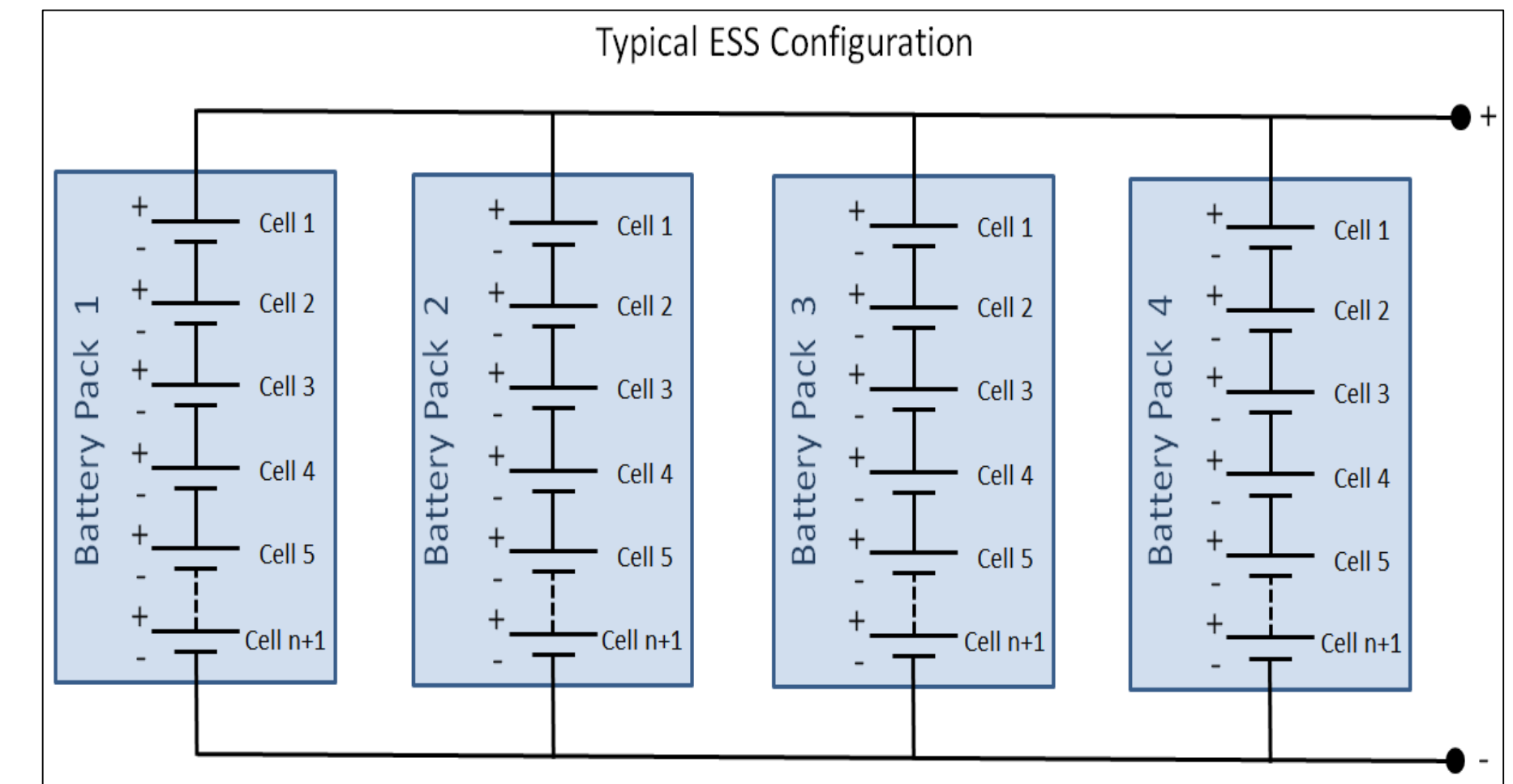
Electrical Risks

Live Potential of Batteries

- ESS (Energy Storage System) are impossible to fully shut down
- Safety cannot rely only on contactors

Multiple Sources

- ESS are built by plugging multiple battery packs in parallel
- Multiplied cabling throughout the vehicle
- A single battery pack presents the same risk of electrocution as exposure to the full potential of the ESS
- Decommissioning is not complete until all sources are disconnected

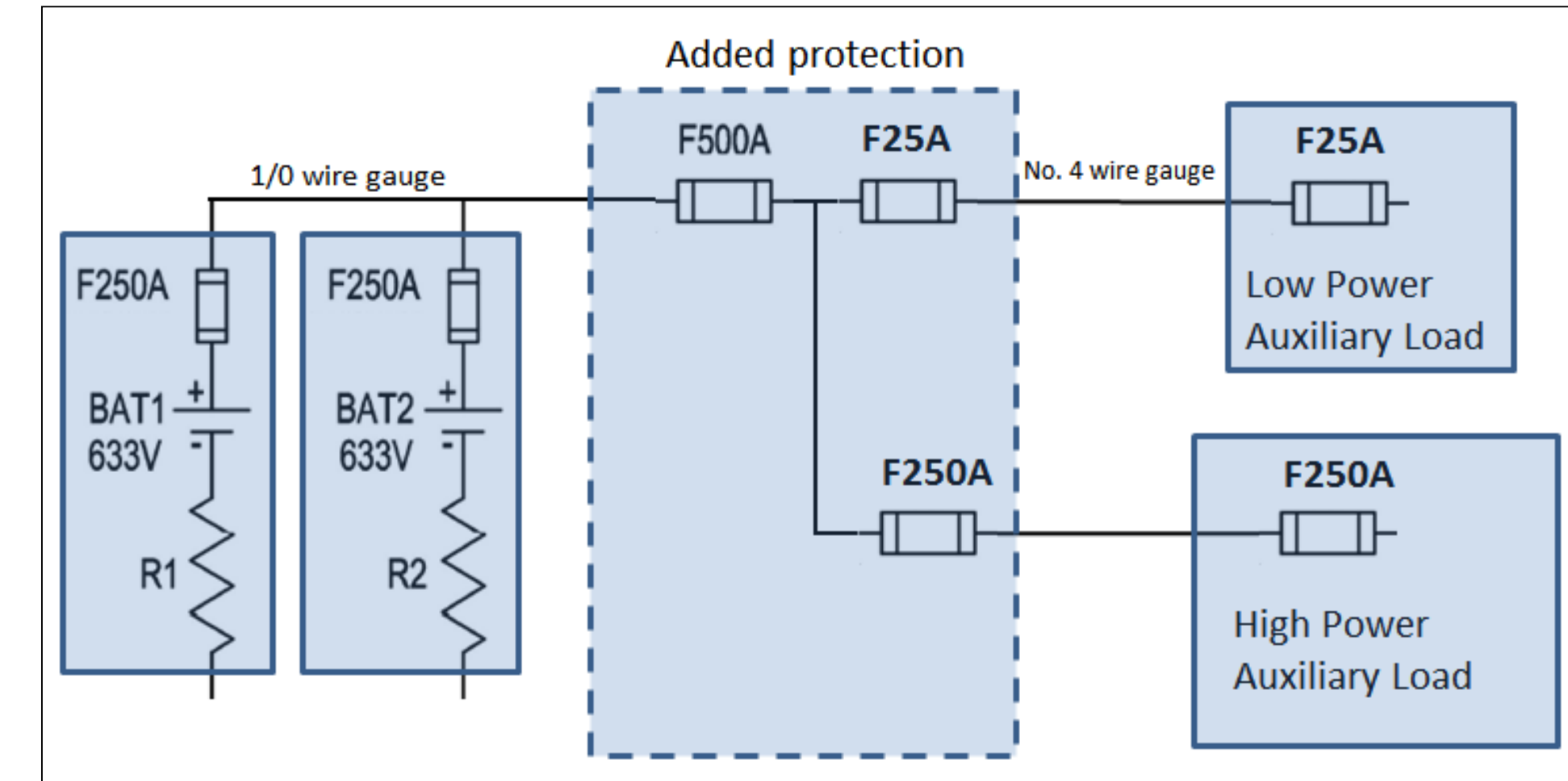




Electrical Risks

Level of Energy

- High level of energy allows very high currents
- Proper fusing, not only within system components but also for cabling
- Parallel sources may bring high currents to smaller gauge wires
- Short circuits could exist and lead to a fire in the cabling and/or vehicle
- Thermal runoff of battery cell
- High current detection shall be implemented in the ESS BMS





Electrical Risks

High Voltage

- 700-volt level falls within the category of high voltage
- Electric shock

Arc Flash

- Combination of large amount of current and high voltage
- Category Type II or III for ESS-equipped vehicles

Human Factor

- Overconfidence
 - No noise
 - No moving parts
- Lack of training
- Lack of training program





Design for Safety

Safety revolves around two basic principles

Passive Safety

- Mid-pack disconnects
- Right fusing strategy and wire gauges
- Touch-proof connectors
- Mechanical designs that limit access to HV components
- Detection of unplugged cables
- Keyed connectors
- Minimized cable lengths
- State of the art cable routings
- Poka-yoke lug sizes to prevent swapping
- Etc.

Active Safety

- HVIL (High Voltage Interlock Loops)
- Current leak detection and intervention
- Multi-pole battery contactors
- Etc.





Electrical Safety of Heavy Duty Transit Buses

Risk Calculation and Mitigation

- The nonexistence of zero risk is admitted in theory
- In practical terms, no one wants to be exposed to risks
- Having infinitesimal probability of defect occurrence is the challenge



Electrical Safety of Heavy Duty Transit Buses

Example: probability calculation of human exposure to high voltage

Safety can then be determined through mathematical probability

1. List passive and active safety features

Active and Passive Safety Features and Systems
HVIL
Internal battery contactors (both poles)
Voltage leak detector (hot coach)
Contactor state measurement
No use of chassis ground for current return (HV)
No easy accessibility to live potential
Galvanic isolation between HV and low voltage circuit
Shielded power cables
Common chassis ground for all components
Manual service disconnect
Unplugged battery connector(s)
Use of HV protective gloves
Isolated pole caps
Finger proof connectors
Work and safety instructions
Training and certification

2. Establish vehicle states

Vehicle States
In operation
Maintenance or repair
Troubleshooting (live HV)
Under construction / assembly
Battery transportation
Emergency intervention / accident

Safety features may or may not be operational or efficient depending on whether the vehicle is in operation or under construction or maintenance



Electrical Safety of Heavy Duty Transit Buses

Example: probability calculation of human exposure to high voltage

Combining active and passive safety features with vehicle state

Vehicle State	Active Safety	Level of Safety	Passive Safety	Level of Safety
In operation	HVIL Internal battery contactors (both poles) Voltage leak detector (hot coach) Contactor state measurement	Medium	No use of chassis ground for current return (HV) No easy accessibility to live potential Galvanic isolation between HV and low voltage circuit Shielded power cables Common chassis for all components	High
		Medium		High
		Medium		High
		Low		High
Maintenance or repair	HVIL Internal battery contactors (both poles) Voltage leak detector (hot coach) Contactor state measurement		Manual service disconnect	n/a
			Unplugged battery connector(s)	n/a
			Use of HV protective gloves	n/a
			Isolated pole caps	n/a
Emergency intervention/accident	HVIL Internal battery contactors (both poles) Voltage leak detector (hot coach) Contactor state measurement		Finger proof connectors	n/a
			Work and safety instructions	Medium
			Training and certification	Medium
Vehicle State	Active Safety	Level of Safety	Passive Safety	Level of Safety
In operation	HVIL Internal battery contactors (both poles) Voltage leak detector (hot coach) Contactor state measurement	Medium	No use of chassis ground for current return (HV) No easy accessibility to live potential Galvanic isolation between HV and low voltage circuit Shielded power cables Common chassis for all components	High
		Medium		n/a
		Medium		Medium
		Low		Low
Maintenance or repair	HVIL Internal battery contactors (both poles) Voltage leak detector (hot coach) Contactor state measurement		Manual service disconnect	Medium
			Unplugged battery connector(s)	High
			Use of HV protective gloves	High
			Isolated pole caps	Medium
Emergency intervention/accident	HVIL Internal battery contactors (both poles) Voltage leak detector (hot coach) Contactor state measurement		Finger proof connectors	n/a
			Work and safety instructions	Medium
			Training and certification	Low
				Low
Vehicle State	Active Safety	Level of Safety	Passive Safety	Level of Safety
In operation	HVIL Internal battery contactors (both poles) Voltage leak detector (hot coach) Contactor state measurement	Low	No use of chassis ground for current return (HV) No easy accessibility to live potential Galvanic isolation between HV and low voltage circuit Shielded power cables Common chassis for all components	High
		Low		Medium
		Low		Low
		Low		Low
Maintenance or repair	HVIL Internal battery contactors (both poles) Voltage leak detector (hot coach) Contactor state measurement		Manual service disconnect	High
			Unplugged battery connector(s)	High
			Use of HV protective gloves	High
			Isolated pole caps	High
Emergency intervention/accident	HVIL Internal battery contactors (both poles) Voltage leak detector (hot coach) Contactor state measurement		Finger proof connectors	n/a
			Finger proof connectors	n/a
			Finger proof connectors	n/a
			Training and certification	Low

- The reliability or defect rate of each feature or system is established and categorized. A defect rate of 1.E-06 (1/1,000,000) is assigned to a HIGH level of safety, one of 1.E-05 (1/100,000) to a MEDIUM level of safety, and one of 1.E-04 (1/10,000) to a LOW level of safety.



Electrical Safety of Heavy Duty Transit Buses

Example: probability calculation of human exposure to high voltage

Vehicle State: In operation	Probability of HV Exposure
HVIL	1E-05
Internal battery contactors (both poles)	1E-05
Voltage leak detector (hot coach)	1E-05
Contactor state measurement	1E-04
No use of chassis ground for current return (HV)	1E-06
No easy accessibility to live potential	1E-06
Galvanic isolation between HV and low voltage circuit	1E-06
Shielded power cables	1E-06
Common chassis for all components	1E-06
Manual service disconnect	1E+00
Unplugged battery connector(s)	1E+00
Use of HV protective gloves	1E+00
Isolated pole caps	1E+00
Finger proof connectors	1E+00
Work and safety instructions	1E-05
Training and certification	1E-05
Total Probability	1E-59

Vehicle State: Maintenance or repair	Probability of HV Exposure
HVIL	1E-05
Internal battery contactors (both poles)	1E-05
Voltage leak detector (hot coach)	1E-05
Contactor state measurement	1E-04
No use of chassis ground for current return (HV)	1E-06
No easy accessibility to live potential	1E+00
Galvanic isolation between HV and low voltage circuit	1E-05
Shielded power cables	1E-04
Common chassis for all components	1E-05
Manual service disconnect	1E-06
Unplugged battery connector(s)	1E-06
Use of HV protective gloves	1E-05
Isolated pole caps	1E+00
Finger proof connectors	1E-05
Work and safety instructions	1E-04
Training and certification	1E-04
Total Probability	1E-69

Vehicle State: Emergency intervention/accident	Probability of HV Exposure
HVIL	1E-04
Internal battery contactors (both poles)	1E-04
Voltage leak detector (hot coach)	1E-04
Contactor state measurement	1E-04
No use of chassis ground for current return (HV)	1E-06
No easy accessibility to live potential	1E-05
Galvanic isolation between HV and low voltage circuit	1E-04
Shielded power cables	1E-04
Common chassis for all components	1E-06
Manual service disconnect	1E-06
Unplugged battery connector(s)	1E+00
Use of HV protective gloves	1E+00
Isolated pole caps	1E+00
Finger proof connectors	1E+00
Finger proof connectors	1E-04
Training and certification	1E-04
Total Probability	1E-55

The total composite probability of exposure to HV is then calculated as follows:

$$P(A \cap B \cap C \cap \dots n) = P(A) \times P(B) \times P(C) \times \dots P(n)$$



Electrical Safety of Heavy Duty Transit Buses

Conclusions

- High safety level is achieved for various use cases of the vehicle
- Safety risk levels vary with feature activation and are influenced by usage context
- Safety shall be built by adding and cascading layers of protection rather than working solely on a single system
- Unlike what is sometimes seen in standards, the safety approach cannot be solely based on single failure mode
- The methodology used here can also be applied to measure safety relative to high currents and thermal runoff
- A complete safety approach integrates and combines standards such as SAE J2910, FMEA analysis and risk calculations based on safety features

An HV protection contactor may yield a defect probability of

$$P = 1.E-05 \text{ (1/100,000)}$$

**Without safety feature combination,
a high risk still exists**



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