High Voltage Safety

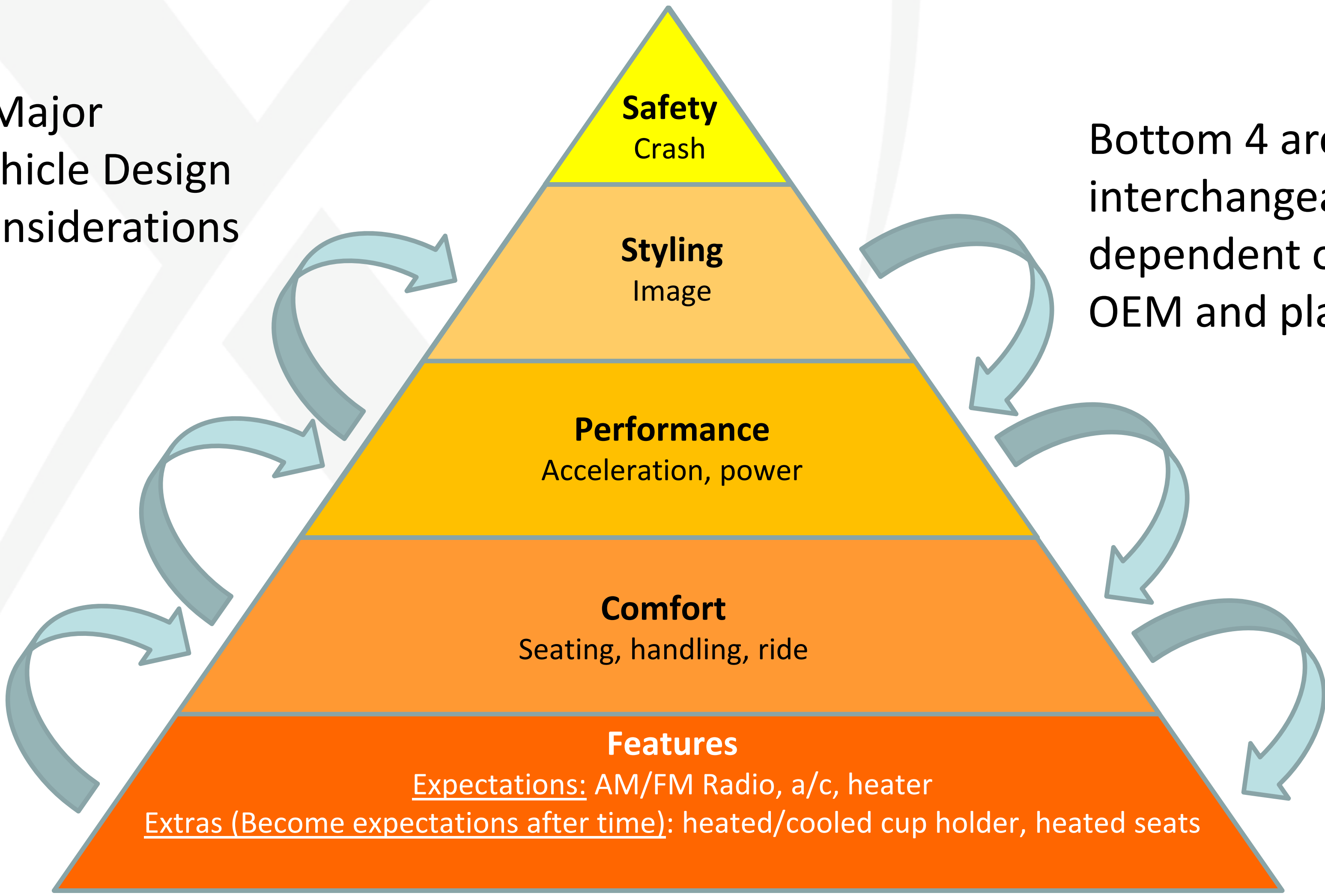
Jody J. Nelson, Sr. Advisor, Energy Storage Technologies

Overview

- Importance of HV safety
- HV isolation from vehicle chassis – requirement
- Discuss HV safety switch requirements
- Highlight e-drive related First Deliverable requirements

Why Spend So Much Time on Safety?

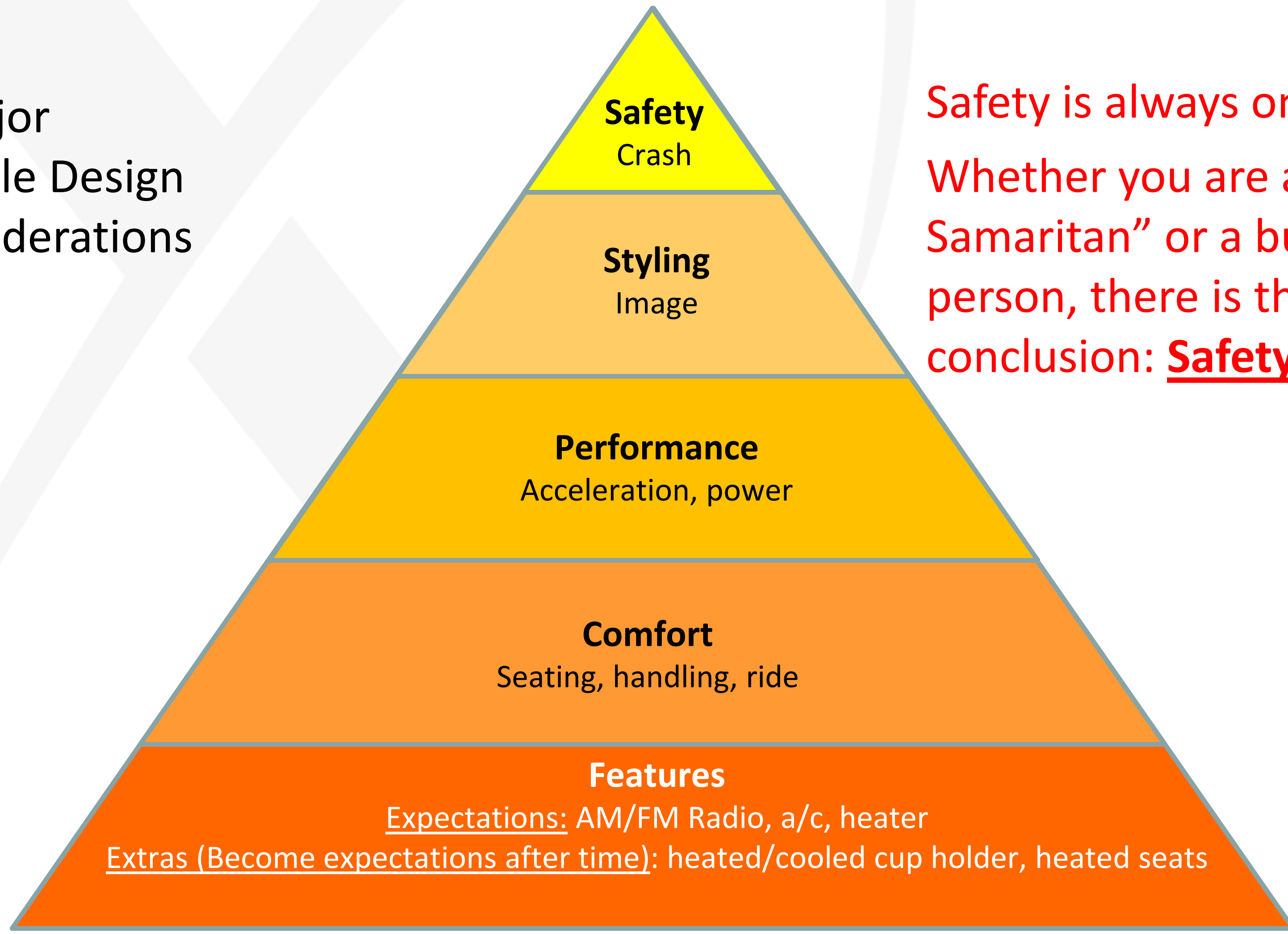
5 Major
Vehicle Design
Considerations



Bottom 4 are
interchangeable
dependent on
OEM and platform

Same Conclusion – Safety First

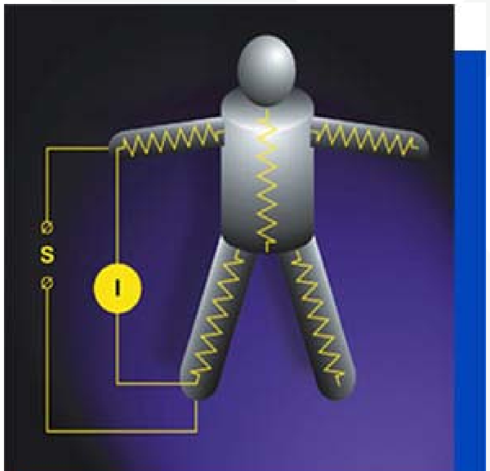
5 Major
Vehicle Design
Considerations



Safety is always on top:

Whether you are a "Good Samaritan" or a business person, there is the same conclusion: **Safety First**

Why is HV Safety Stressed So Much?



http://www.data-input.de

A number of factors influence the human body resistance, but IEC has provided 1 kΩ as an average value

Bodily Effect	dc Current [mA]
Feeling Sensation	1.0
Pain is Felt	62
“Let-Go” Threshold	76
Severe Pain; Breathing Difficulties	90
Heart Fibrillation Occurs	500

12 mA @ 12 V

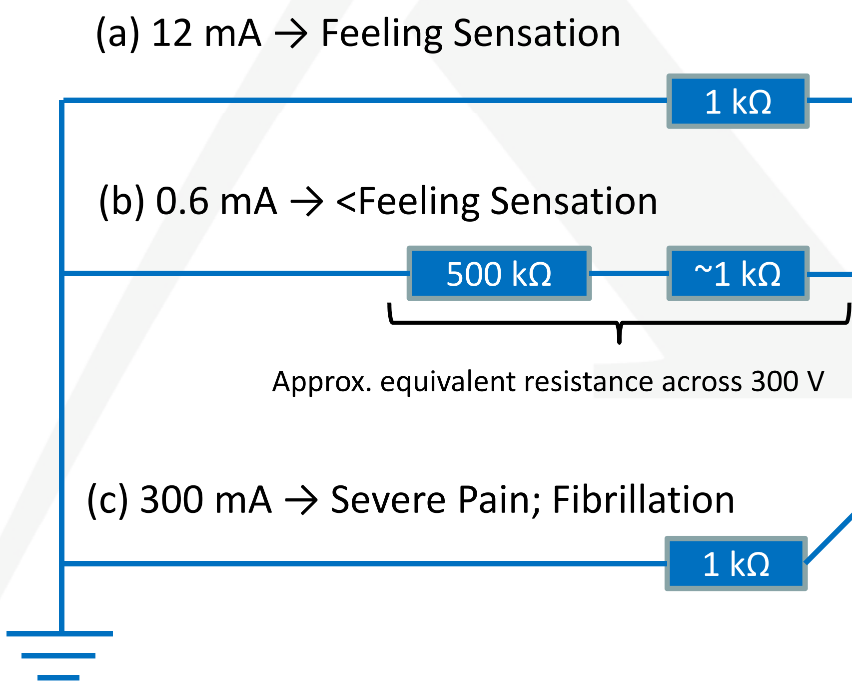
300 mA @ 300 V

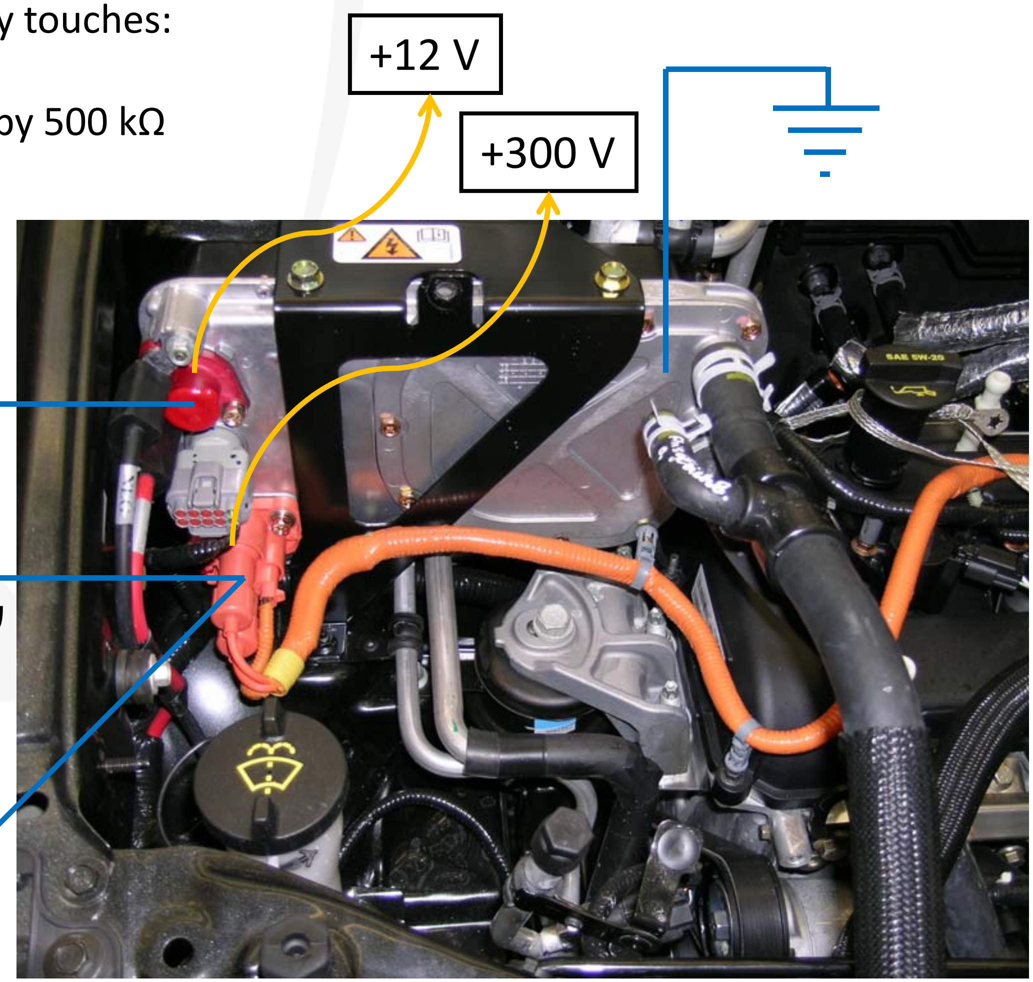
Note: @50 V, body currents are 50 mA. Anything over 50 V must be considered High Voltage

Real Case Scenario

<u>Scenario:</u> Working on dc/dc converter, left hand holding case of converter (ref. to chassis), right hand accidentally touches:

(a) +12 V post
(b) +HV terminal with HV isolated from chassis by 500 kΩ
(c) +HV terminal with -HV referenced to chassis





Real Event During F1 Testing

During F1 testing in Spain, BMW Sauber mechanic was electronically shocked from the HV KERS (Kinetic Energy Recovery System)

Situation could have been worse if it was not for the low energy capacitive discharge

KERS allows only 400 kJ total energy, equating to 60 kW of power for 6.67 seconds over the entire race

This is a magnitude lower energy than a typical HEV battery!

Safety Equipment

Isolated gloves and safety glasses should be worn at all times when working with the vehicle

Recommended that all Team members have HV safety training: Can seek local National Fire Protection Association (**NFPA**), National Alternative Fuels Training Consortium (**NAFTC**), or others (**OSHA, NEC (NESC), IEEE**) for possible resources/courses

Safety Equipment

All tools used on the electrical system should have non-conductive coatings to prevent accidental contact

Personal Protection Items

Make a list of required safety items for working on the vehicle:

- ❑ Flash suit
- ❑ Face shield / hard hat
- ❑ Insulated tools
- ❑ Safety glasses / ear plugs
- ❑ Hot stick
- ❑ Rubber gloves with leather protectors
- ❑ DVM / Tic Tracer
- ❑ Grounding stick
- ❑ Protective grounds
- ❑ Insulation blankets
- ❑ EH rated shoes
- ❑ Buddy system

Lock-Out, Tag-out

- In the workplace always have lock-outs on items with a potential safety concern:
  - Lock-out/de-energize high voltage equipment before debugging, working, or installing new equipment
  - Ensures that only qualified people are working on the vehicle
  - Minimizes the chance of injury for curious “passers-by” when nobody is around
- LOTO (Lock-Out, Tag-out) examples:
  - Manual Isolation Switch (MIS) in your vehicle (at night put the MIS in a locked toolbox)
  - Power source for test equipment (line power, power supply, etc)
- Authorized personnel: Only authorized personnel who are aware of the high voltage dangers should work on HV equipment

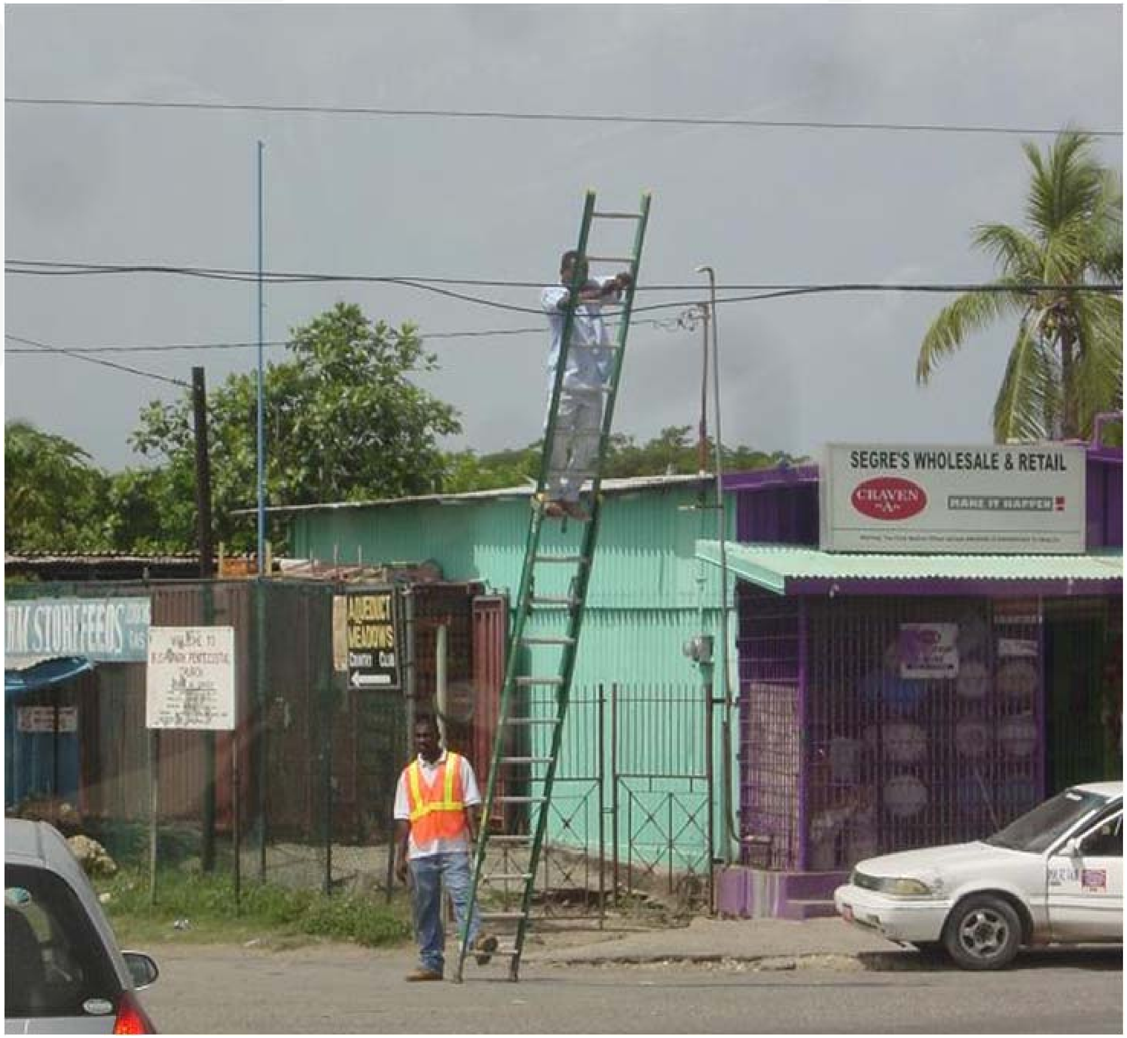
Lock-Out/Tag-Out Devices

Lockable plug covers

Covers for sharp ends (pointy guards)

Circuit breaker lockable covers

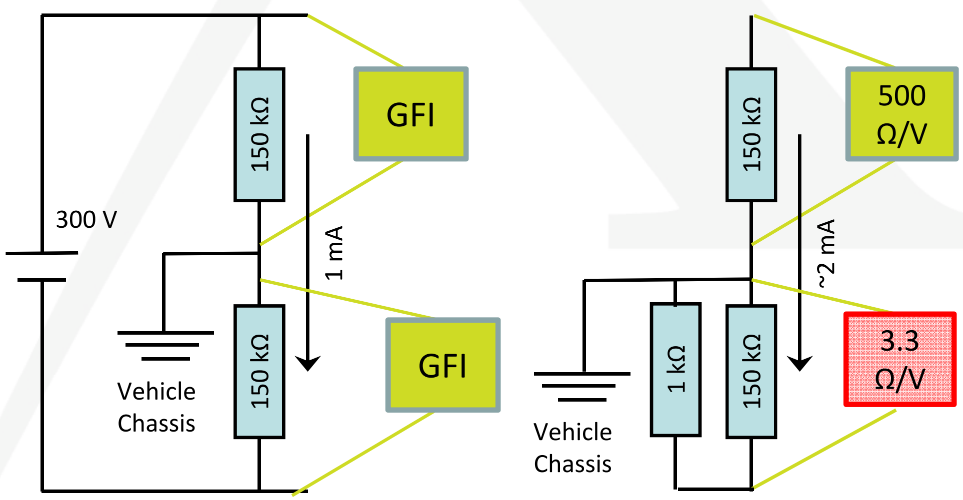
Use Common Sense When Working on HV



GFI – Loss of Isolation Detection

The Ground Fault Isolation (GFI) detection must properly signal loss of isolation, and clearly be shown to the driver, when the electrical isolation becomes < 500 Ω/V, where V is equal to the nominal voltage of the traction battery

- Difficult to achieve with current sensors: A LEM sensor with 1% accuracy cannot sense a 1 mA change, i.e., at 200 A already could have a 2 A error
- Can be achieved with precision resistors and Op-Amp circuit
- Recommendation from Technical Specification: Bender IRDH275 meter with an adjustable response isolation resistance from 1 kΩ to 10 MΩ

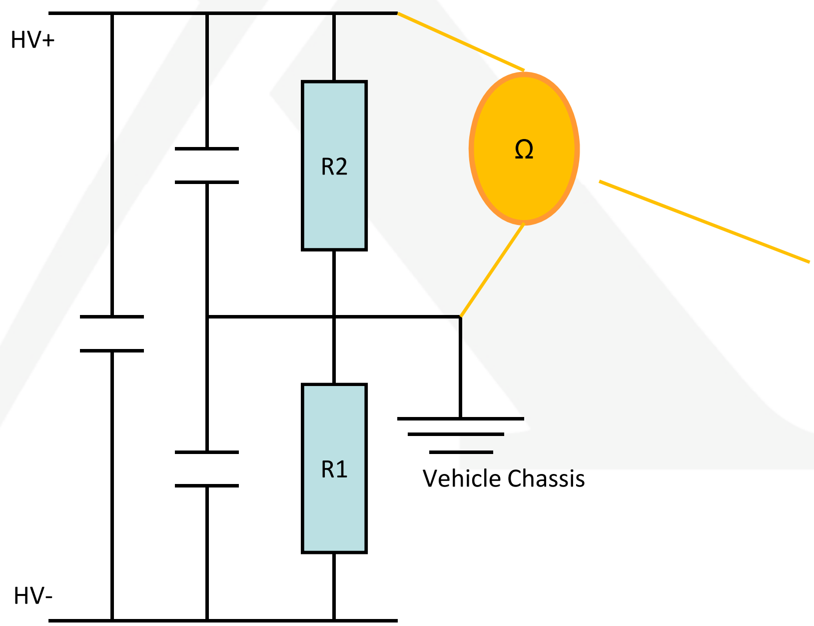


Measuring Isolation Resistance

Test Case: Vehicle powered off, all HV components connected, using an ohm meter measure the equivalent resistance between the HV bus and vehicle chassis

HV positive to vehicle chassis: R2 = Ω

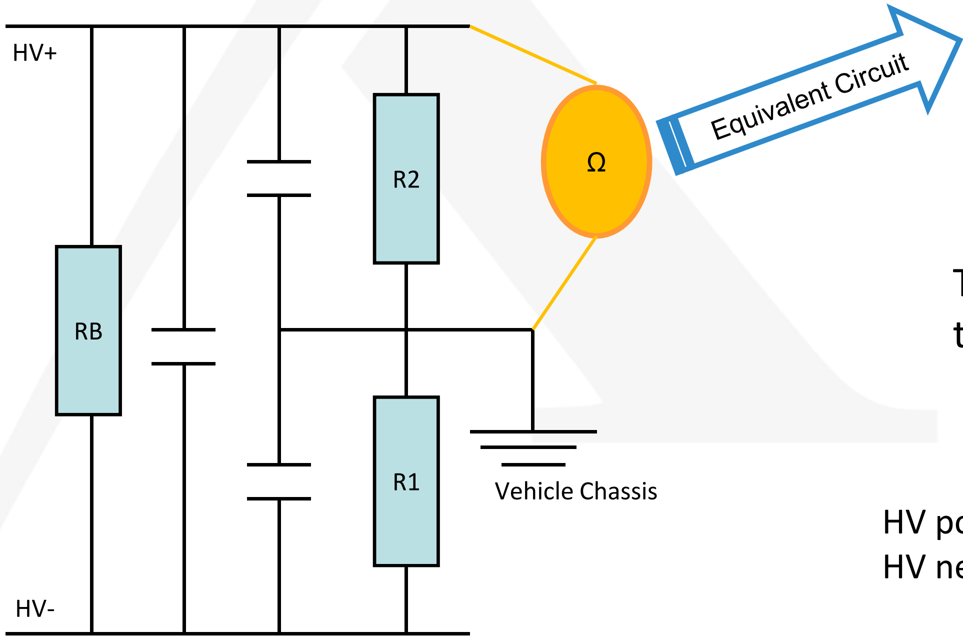
HV negative to vehicle chassis: R1 = Ω

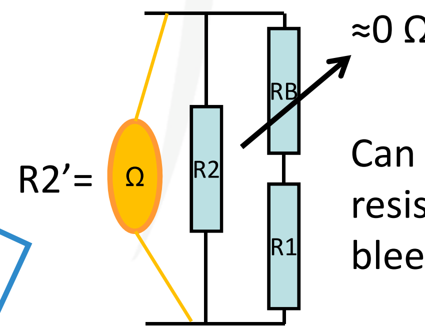


Where R1 and R2 are equivalent resistances of the entire system, but understand your complete HV circuit first….

Measuring Isolation Resistance

…but generally there is a passive bleed resistor (RB ≈ 10’s kΩ) across the HV bus to discharge the bus in some minutes after the vehicle is powered down…thus the circuit becomes…





Can approximate if isolation resistance is much larger than bleed resistor:

R1≈ R2 >> RB

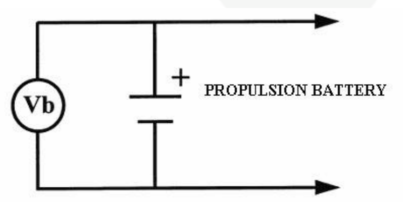
Thus, measuring across R2 yields half of the actual R2 (R1||R2 ≈ R2’):

HV positive to vehicle chassis: R2 ≈ 2*R2’ Ω

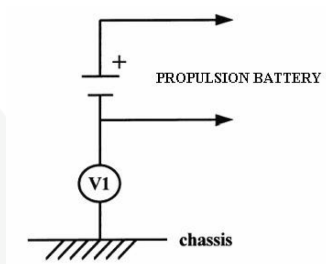
HV negative to vehicle chassis: R1 ≈ 2*R1’ Ω

Measuring Isolation FMVSS 305/SAE J1766

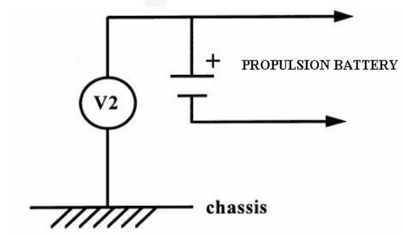
Vehicle inspections will be conducted according to FMVSS 305:



Step 1: Measure bus voltage
Vb must be nom. V or greater

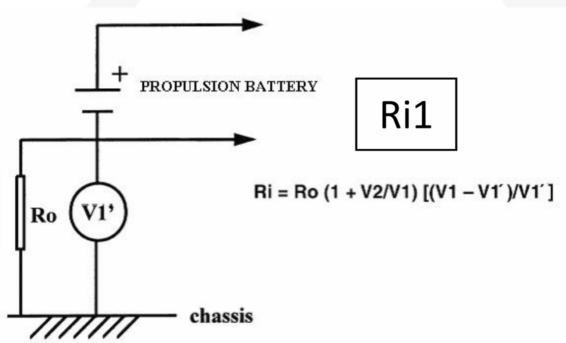


Step 2: Measure HV- to chassis

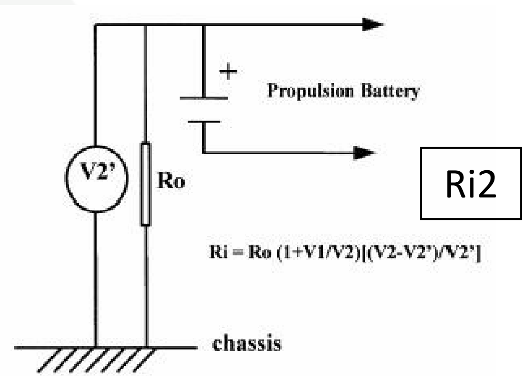


Step 3: Measure HV+ to chassis

Ri = lesser of Ri1
& Ri2



Step 4: Measure HV- to chassis
with Ro (500 x Vb)



Step 5: Measure HV+ to chassis
with Ro (500 x Vb)

Ri/Vb ≥ 500 Ω/V

Equipotential Bonding

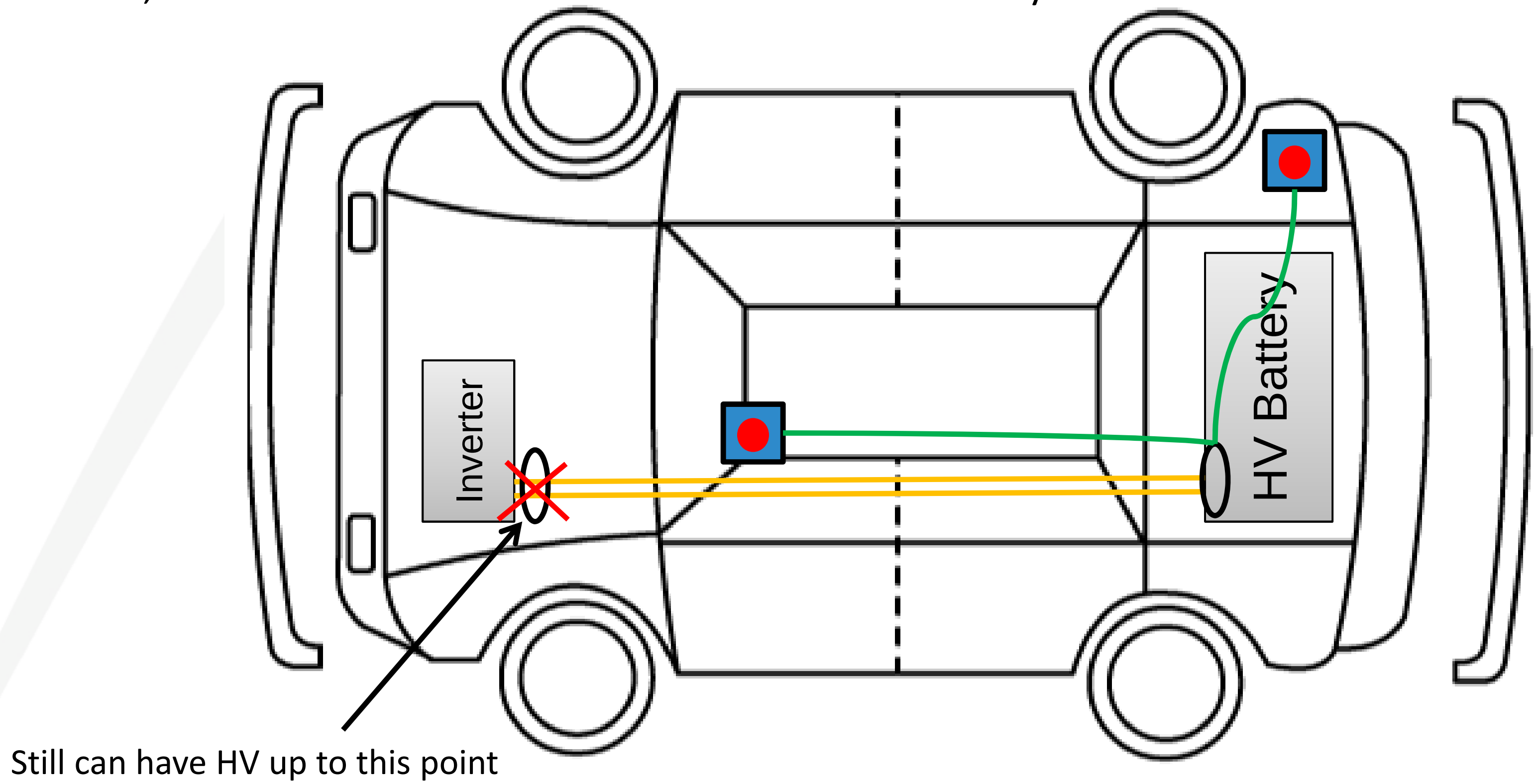
All HV components enclosed by conductive casing must have equipotential (conductive) bonding between other conductive enclosed casing and vehicle chassis

The maximum allowable resistance of the bonding is 0.1 Ω

Without this, the GFI becomes useless in an event when the HV is shorted to the conductive case; Since the case is floating, the GFI cannot detect loss of isolation to the vehicle chassis

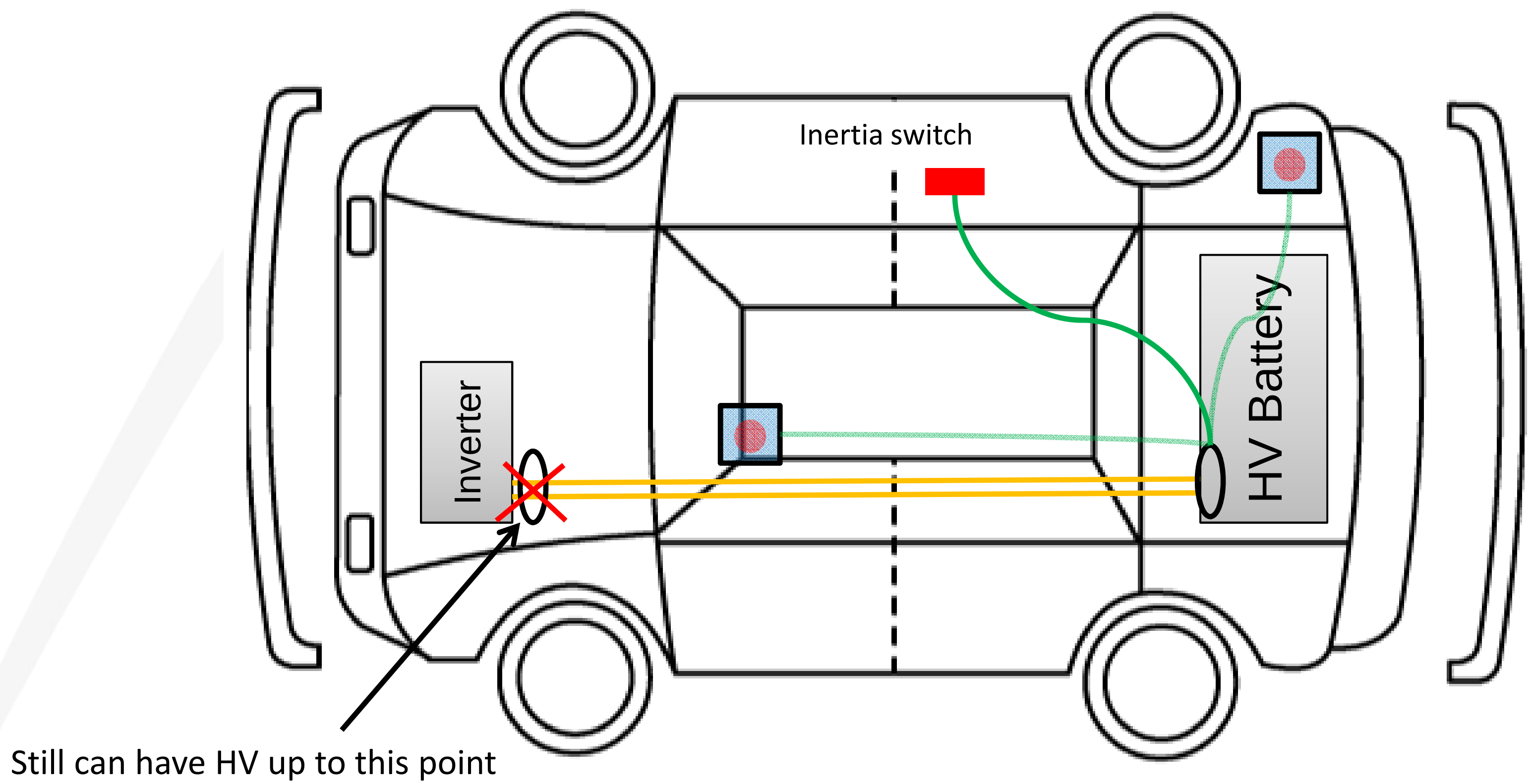
EDS (e-Stop Button)

Emergency Disconnect Switches (EDS) are required in the event of a run-away condition or other unsafe situations. It is required at full-load to safely and immediately disconnect the HV source from the remainder of the vehicle. The EDS contactor should be located, ideally, within the HV battery case, otherwise not to exceed 3 feet from the HV battery.



Inertia Switch

The Inertia Switch should activate the EDS to open the HV circuit in the event of an accident exceeding an acceleration of 8 G

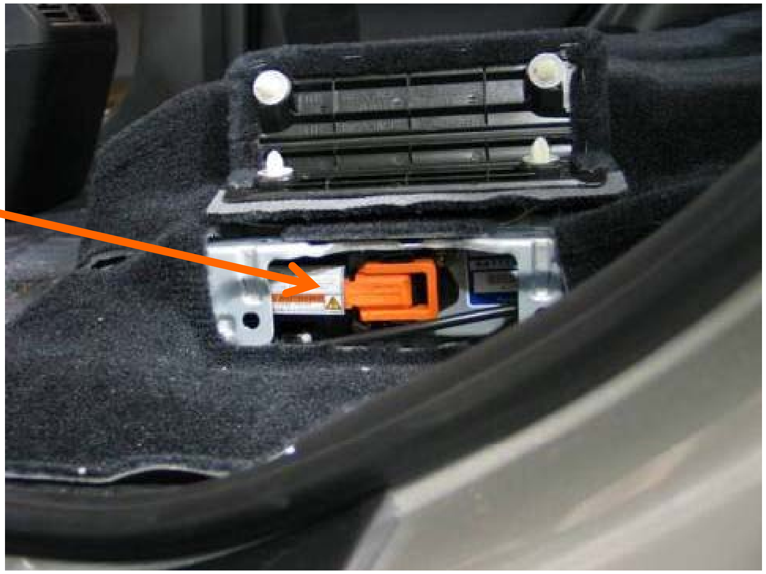


MIS (Service Switch)

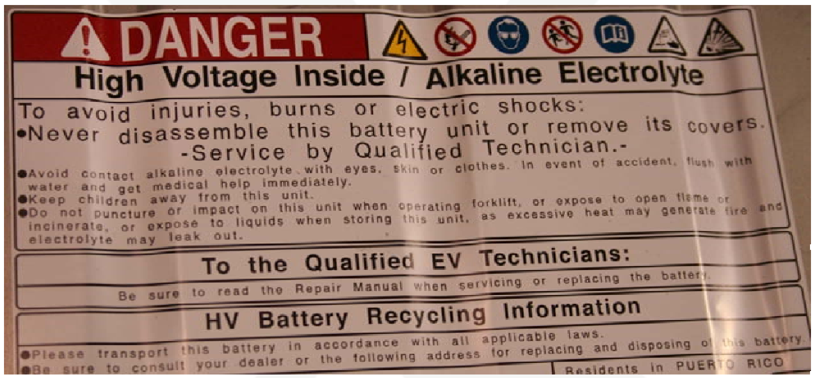
A Manual Isolation Switch (MIS) is required to disconnect the HV from the system to allow for working on the vehicle safely

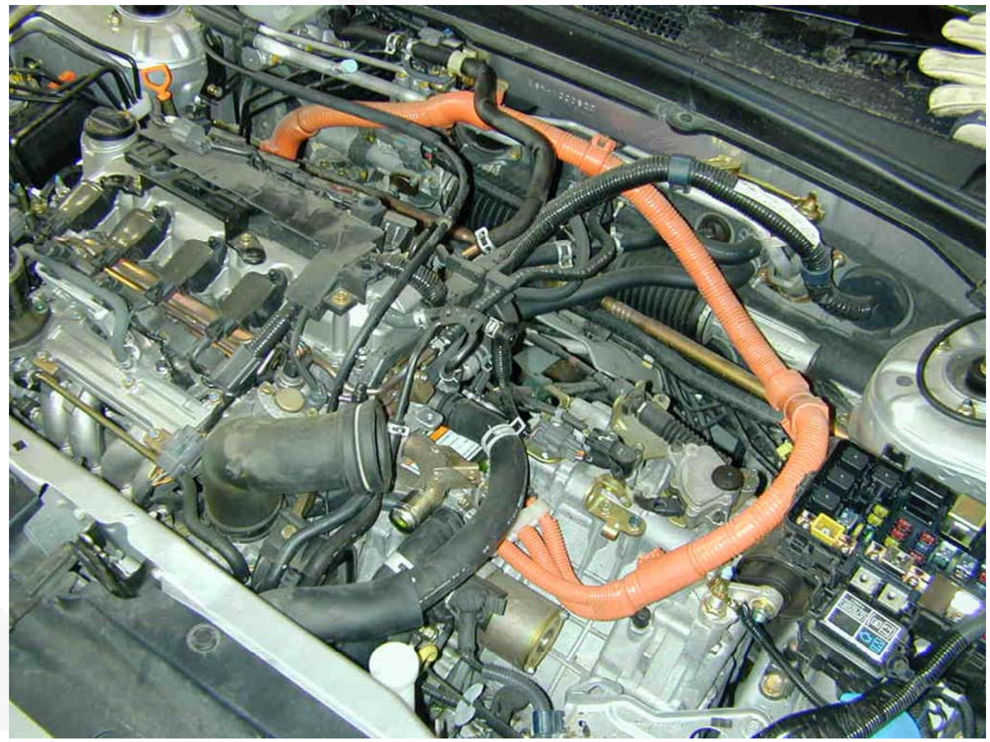
- The MIS switch should be after the EDS in the event the EDS was deployed so that there remains no voltage at the terminals of the MIS
- The MIS must be disconnected by physically pulling and separating (not by electric actuation) the contacts or terminals that lead to the high-voltage system
- The MIS is not intended to open the HV circuit under load

Common for current production HEVs to have MIS located directly on the HV battery



Warning Labels





- Orange cables easy to see
- Warning labels on all HV components

Environmental Requirements

Make the assumption that it will be raining at MIS during some of the events

Be certain to make all preventive measures on all HV components so that they are safe from rain and accidental spills (the soda pop spill test)

Be aware of common environmental test for OEMs:

- Low/high temperature endurance
- Thermal cycles
- Thermal shock
- Humidity endurance
- Solar radiation
- Vibration
- Mechanical shock
- Handling drop test
- Dust (DIN-40-050)
- Water intrusion
- High pressure steam jet exposure (DIN 40-050)
- Salt water immersion
- Salt fog

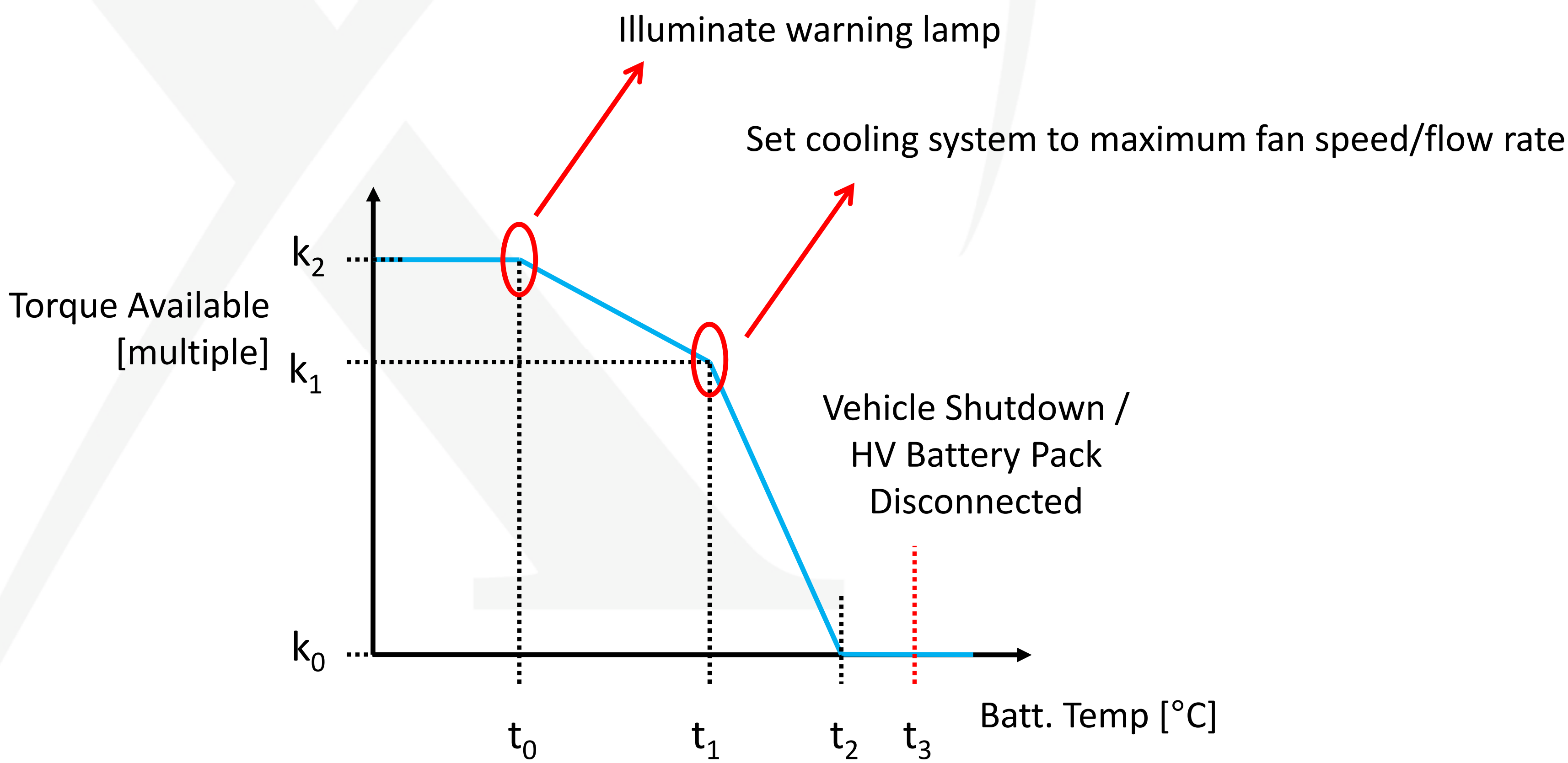
HV Battery Thermal Management System

1. Documentation: Teams shall provide documentation of their battery temperature management strategy and provide a test plan illustrating how their design will be tested on the vehicle. First Deliverable
2. Testing: Teams are required to demonstrate their design works as intended with the proper vehicle reaction based on their test plan. Second Deliverable

The test plan should include:

- Vehicle operating state; i.e. idle
- Description of how the battery temperature will be simulated:
    - Pulling a thermocouple off and heating it externally (D-4.4.8)
    - Using SW to change the temperature parameter
- The simulated temperature should be step or linear increases up to the maximum rated temperature
- Teams should include expected vehicle reaction at every defined temperature threshold

Example HV Battery Thermal Management



Example: Thermal Management Failure

PROGRESSIVE AUTOMOTIVE X PRIZE

Example: Thermal Management Failure

Example: Thermal Management Failure

Erroneous Propulsion and Monitoring

ECE R100 5.2.2.3: "Unintentional acceleration, deceleration, and reversal of the drive train shall be prevented. In particular, a failure (e.g. in the power train) shall not cause more than 0.1 m movement of a standing un-braked vehicle."

Teams shall provide documentation detailing how their control system addresses the issue of erroneous propulsion. Documents should include:

- Vehicle reaction to loss or erroneous values of critical vehicle control signals such as electric motor position, phase currents, voltages, commanded torque signal, throttle position, etc.
- All preventive measures taken to prevent unintentional movement of the vehicle
- Describe monitoring strategy: i.e. if a torque transducer is used to measure torque, how is it verified; i.e. by a calculation. What is the plausibility check for sensors; i.e. how are the current sensor values verified?

Note: For ICE vehicles, FMVSS 124 provides regulation of ICE up to WOT when an Accelerator Throttle Position Sensor, Electronic Control Module, Throttle Plate Actuator Motor, and Throttle Plate Position Sensor are disconnected

Erroneous Propulsion – Example Test

To test for unintentional movement of the vehicle, the following test can be performed:

- Place running vehicle in neutral on a flat, smooth surface; vehicle should not move
- If using a PM motor, apply maximum I_D current at 0 I_Q current; vehicle should not move more than 10 cm
- If using an accelerator potentiometer, create an open and short circuit of the "throttle-by-wire"; vehicle should not move more than 10 cm

Vehicle Diagnostics

In production vehicles, diagnostics make up **80%** of the SW whereas the actual propulsion code is only around 20%

The Judging Panel considers vehicle diagnostics an essential requirement of all vehicles

It is required in the First Deliverable to describe in detail the protection (fail-safe) strategy for the below conditions

If the Judging Panel is not satisfied with the response, further evidence or visit may be required

Please provide HIL results when possible. Include control diagrams and a software description or hardware schematics:

- HV short-circuit on HV dc and 3-phase ac sides
- How is a short detected? What is the vehicle reaction to a short?
- HV over-current: thresholds, vehicle reaction
- HV over-voltage: thresholds, vehicle reaction
- Over-temperature of the power electronics, electric motors, and HV battery
- Runaway motor (loss of speed sensor)
- Loss of low voltage (supplying your controller)

Vehicle Inspection Preview

- Visual inspection of all electrical components and cables/connectors
  - Fusing, proper connectors, finger-proofing, strain-relief, routing (no chaffing or exposure to sharp edges), closeness to heat sources, waterproofing
- Inspection of all HV safety related switches and isolation detection
- Resistance measurement of all conductive HV enclosures to the vehicle chassis
- Inspection of HV battery and thermal management system
- EDS will be tested under load
- Vehicle isolation will be checked per FMVSS 305 requirements
- Removal of the 12 V power source while vehicle is operating
- Various diagnostic features will be tested

Summary

- **All vehicle designs are centered around safety**
  - ❑ Will be first priority in vehicle inspections
- **Accidental contact of high voltage can lead to dangerous body currents**
  - ❑ Takes < 100 mA to be very dangerous
- **The vehicle chassis must be isolated from the HV bus and must be monitored at all times**
  - ❑ Will be tested during vehicle inspections: must meet FMVSS 305
- **There are a number of required HV safety switches called out in the technical specification**
  - ❑ Must address all questions in First Technical Deliverable
- **HV battery safety and thermal management are critical considerations in the competition**
  - ❑ First Technical Deliverable must provide test plan; Second Technical Deliverable must provide test results
- **Teams should be aware of fault and over-limit conditions and should deal with them properly**
  - ❑ First Technical Deliverable must provide details of diagnostics