Clarifications to Questions Raised at 2nd Stakeholders Meeting on Fault Tree Analysis

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What Level of Risk is Acceptable?

- Comment that new technologies need to provide a safety level at least equal to the technologies they replace
  - Long recognized that there is “no easy answer”; to meet GWP requirements either toxicity or flammability risk will have to be increased
    - R-1234yf is better than R-134a for GWP, similar for toxicity but slightly flammable
    - R-744 (CO2) is not flammable but has increased toxicity and decreased performance relative to R-134a
  - Overall, there is a net benefit of replacing R-134a by R-1234yf
  - The increase in risk for particular concerns (e.g., flammability) needs to be and is small enough to be acceptable, i.e., consistent with relevant regulations or standards or commonly accepted practices

- Comment that R-1234yf safety should be “practically equivalent” to R-134a
  - SAE CRP1234-4 considers this to mean any increase in risk is small enough to be considered to be acceptable in light of regulatory frameworks and public perception
  - Objecting to any increase in risk is unworkable
    - Impossible to satisfy multiple objectives (toxicity, flammability, GWP, regulatory requirements, performance)
  - A requirement for “no increase in risk” requires that the method used to assess risk must be infinitely precise, an impossibility

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The Appropriate Top Event

- Comment that a vehicle fire caused by the refrigerant is a more appropriate top event
  - SAE CRP1234 determined that a vehicle fire *with someone present* was the appropriate top event
  - Vehicle fires may not necessarily result in harm, people will seek to exit the vehicle prior to being harmed if able to do so
  - Risk of exposure to a fire and risk of a fire are not interchangeable
    - In the CRP analysis, risk of vehicle fire is highest for medium speed front collisions, a collision type with a low risk of entrapment/potential exposure
    - The risk of vehicle fire is correspondingly lower for side collisions which do have a higher risk of entrapment/potential exposure
- However, requests by some German OEMs (prior to leaving the CRP) led to development of fault tree structures that can also estimate the frequency of vehicle fire (next slide)

Additional Results from CRP1234-4 Analysis

	Risk (per operating hour)	Margin of Exposure
CRP1234 - Risk of exposure to R-1234yf related vehicle fire	3×10^{-12}	
Background risk of injury or fatality from a vehicle fire	3×10^{-8}	10,000
Background risk of fatality in a regularly scheduled plane trip in a developed nation	7×10^{-8}	23,000
CRP1234 - Risk of R-1234yf related vehicle fire	5×10^{-10}	
Background risk of a vehicle fire (any cause)	1×10^{-6}	2,000

- Margin of Exposure – an approach for comparing an estimated level of exposure to some reference level

  MoE = estimated occurrence/exposure ÷ reference level (e.g., background)

- The larger the Margin of Exposure, the greater certainty that exposure risk is acceptable
- Used by regulators (e.g., the EU Food Safety Authority) to evaluate risks for regulatory acceptability
- Risks estimated for R-1234yf in terms of both exposure and vehicle fires are well below those associated with relevant comparison events

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How Conservative Should You Be?

- Comment that risk assessments must use a conservative approach
  - This is generally recognized, however:
    - Conservatism must not only be acknowledged but its presence must also be fully reflected in how the resulting numbers are used and interpreted
      - For highly conservative assessments, risks must be acknowledged as worst-case and possibly implausible
      - The impact of conservative assumptions should be quantitatively evaluated if possible
      - Conclusions of the risk assessment should reflect real-world relevance
  - Moreover:
    - Excessive conservatism must also be avoided
      - Can create improper barriers to taking action
      - Overly simplified, conservative analyses run the risk of neglecting important elements
      - Failure to study all possible contributing factors can lead to:
        - A failure to fully understand the problem
        - An unrealistic estimate of risk

How Conservative Should You Be? (2)

- Example: CRP1234 did not assume all refrigerant ignition events will automatically result in a vehicle fire
  - Lead us to questions about how refrigerant ignition could lead to a vehicle fire and what factors could intervene and how these might differ by scenario
  - Resulted in further testing, analysis, and data collection
  - Where information was not obtainable (e.g., the effect of oil atomization on propagation), a conservative value (0.99) was used
  - Outcome: The overall probability of "propagation" used by CRP1234 (0.23 to 0.73 depending on crash type) is still conservative but incorporates a better understanding of the scenario

How Conservative Should You Be? (3)

- Comment that lacking a test which exactly replicates real world conditions requires assuming a worst case
  - Lack of perfect tests with which to evaluate real world accident conditions should not be a reason for assuming the worst case occurs always or has relevance for real world
    - In any field/situation, no test can adequately cover all situations, scientists and regulators rely on reasonably appropriate tests
  - Testing conducted by KBA (levels 1 and 2) must come very close to the very worst case situation
    - Worst case models in terms of highest possible operating temperatures
    - Worst case operating conditions (yielding highest temperatures)
    - Worst case crash situation (AC damage but minimal deformation of under hood area)
    - Worst case release type (vapor release)
    - Added damage beyond what was observed in crash tests (KBA level 2)
  - KBA Level 1 and 2 tests showed no ignition and no significant HF generation

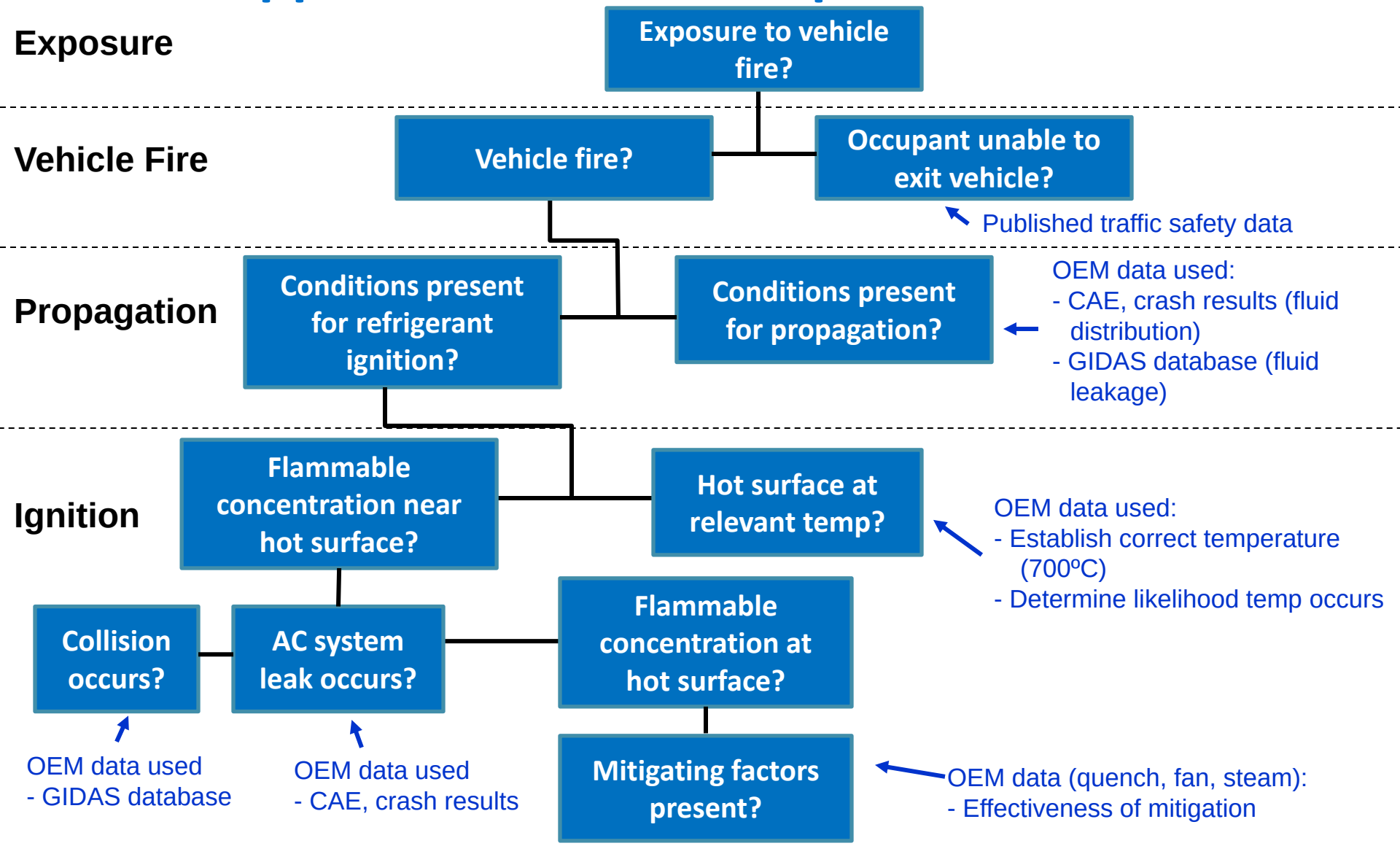
Concerns About "Dilution"

- Comments using the term "dilution" are problematic
  - Including relevant factors that contribute to an event should not be viewed as dilution
- Comment concerning the number of "AND" gates
  - AND gates are used to combine factors which must all occur for an adverse event to take place
  - Considering the full suite of contributing (aggravating/mitigating) factors will make for a stronger analysis rather than a weaker one
  - The only other alternative is to drop potential factors from the analysis which results in loss of useful information
  - Although multiplication of contributing factors (via AND gates) can potentially lead to unwarranted reductions in risk, CRP1234 was very cautious in this regard
    - Mathematical results of AND gates were evaluated for plausibility ("does this overall value seem reasonable?") and when unreasonable, the contributing values were reconsidered

Use of Data and Expert Judgment

- Comment concerning lack of empirical data and use of expert judgment
  - FTA Input values were considered by both experts in automotive AC systems and OEM vehicle safety experts
  - Data was used to support most inputs to the FTA
    - In some cases, the data were taken directly from statistical databases (German GIDAS, US NHTSA)
    - In some cases, they were based on OEM testing and modeling
    - In some cases, the data required interpretation (e.g., for different crash speed ranges/locations)
  - CRP1234 classified all inputs according to 4 categories
    - Category 1: Inputs based on statistical databases
    - Category 2: Inputs based on results of experiments or modeling studies
    - Category 3: Inputs based on theoretical principals or vehicle design features
    - Category 4: Inputs based on expert judgment
  - 84% of CRP1234 FTA inputs were from categories 1 to 3

Data Support Values for FT Input Probabilities



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Interpretation of FTA Results

- Comments concerning robustness and stability of FTA results
- FTA methodology is *specifically designed* to look at risks of unusual, rare failure events requiring multiple combinations of events
- We cannot reject the results because the risks appear too small and could be "invalidated" by a single actual occurrence
  - Represents *post-hoc* analysis (rejecting conclusions because they don't fit with expectations)
- It is appropriate to compare the FTA results to available and relevant data, which CRP1234 did
  - KBA tests, while limited, validate the CRP findings because refrigerant ignition only occurred in one vehicle under extreme conditions which were nonetheless comprehended in the fault tree analysis
  - CRP member tests also were also consistent with FTA results
- It is problematic to use FTA estimates to predict the exact number of events per timeframe (e.g., vehicle fires per year)
  - This is particularly so if the analysis contains highly conservative inputs
  - Attempts to use the risk estimate (i.e., 1×10^{-x}) to predict an actual number of events will lead to erroneously high numbers and incorrect interpretation

Particular Fault Tree Inputs

- Critical Hot Surface Temperature
  - CRP1234 selected a refrigerant ignition temperature (700°C) that was the lower limit of all vehicle testing conducted to date
  - The testing was extensive, involving multiple repeat tests, multiple vehicle models, multiple testing organizations, etc.
  - Selecting a lower ignition temperature (600°C or lower) ignores the available test data
- Engine coolant release
  - The CRP did not assume that engine coolant release always occurs to prevent refrigerant ignition
  - Depending on crash type, the CRP FTA assumed that mitigation from engine coolant will NOT occur in 10% to 95% of cases

HF Generation and Exposure

- KBA testing showed that only 1 vehicle produced significant amounts of HF in the engine compartment (i.e., time weighted averages exceeding the 95 ppm health based limit, AEGL-2)
  - There was no indication of detectable HF concentrations in the passenger compartment
  - This result occurred during refrigerant ignition and under level 3 conditions (i.e., those of unknown plausibility)
- CRP testing of an actual vehicle also indicated that in the absence of R-1234yf ignition, the HF generated was far below the health based limit
- In the CRP testing, even when ignition occurred, HF concentrations in potential exposure areas (in cabin or along vehicle side) were below the health based limit

Summary

1. CRP1234 risk assessment shows that the risks of using R-1234yf in MAC systems are below risks commonly accepted by regulatory authorities and the public
2. A requirement for no increased risk, however minimal, is impractical given competing concerns regarding toxicity, flammability, ODP, GWP, and performance
3. While CRP1234 believes the appropriate top event of interest is exposure to a vehicle fire, the CRP analysis also shows that risk of vehicle fire itself are also well below current risk levels
4. The CRP risk assessment was appropriately conservative but also comprehensive and reflective of real world situations
    - Being thorough and comprehensive is not dilution
    - Excessive conservatism should not become a basis for inaction
5. Inputs for the CRP1234 risk assessment were largely based on extensive data and testing with a limited role for expert opinion
6. This is particularly true for critical inputs such as the hot surface temperature for ignition, the frequency of vehicle collisions and the presence of factors contributing to propagation

Thank you for your attention.