MIXED VOLTAGES AND ALUMINUM CONDUCTORS: ASSESSING NEW ELECTRICAL TECHNOLOGY

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ABSTRACT

The architecture of vehicle electrical systems is changing rapidly. Electric and hybrid vehicles are driving mixed voltage systems, and cost pressures are making conductor materials like aluminum an increasingly viable competitor to copper.

The challenge of assessing the impact of these technologies on vehicle safety and of understanding cost/weight trade-offs is a critical design activity.

This paper presents tradeoff studies at the vehicle level, and how to automatically generate an electrical Failure Mode Effects and Analysis (FMEA) report, as well as how to optimize wire sizes for both copper and aluminum at the platform level.

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W H I T E P A P E R

INTRODUCTION

One approach to reduce the wires sizes, thus saving copper cost and weight, is to use a 48V vehicle harness in place of one or more 12V harnesses. The higher voltage means that a proportionally less current is need for the same amount of power delivered.

Power is defined by the formula: *P=V*I*.

This means if the voltage is increased, less current is needed to provide the same power. The diameter of the wire is largely determined by the amount of current it must carry. With less current in a 48V system, the diameter of the wire can be less, as shown in the following equation, derived from the basic definition of resistivity:

$$csa = \rho * \frac{l * P}{V^2}.$$

Where *CSA* is the cross-sectional area, ρ is the resistivity, *l* is the wire length, *P* is power, and V^2 is the square of the voltage.

Other reasons for using 48V in a vehicle harness beyond the scope of this paper, and it does not it take into account any extra costs for additional batteries. Replacing 12V components with 48V components in a vehicle electrical system also results in changes to the wiring harness. To guaranty the quality and the accuracy of the “new” harness, an FMEA report is a must. FMEA is measuring the risk of failing components and their effect on system functions.

Replacing copper wire with aluminum is also an opportunity to reduce the weight and cost of a vehicle harness. Figure 1 compares the price of copper and aluminum over a three year span. Over that time period, copper exhibits a price difference between 4 and 6 times that of aluminum.

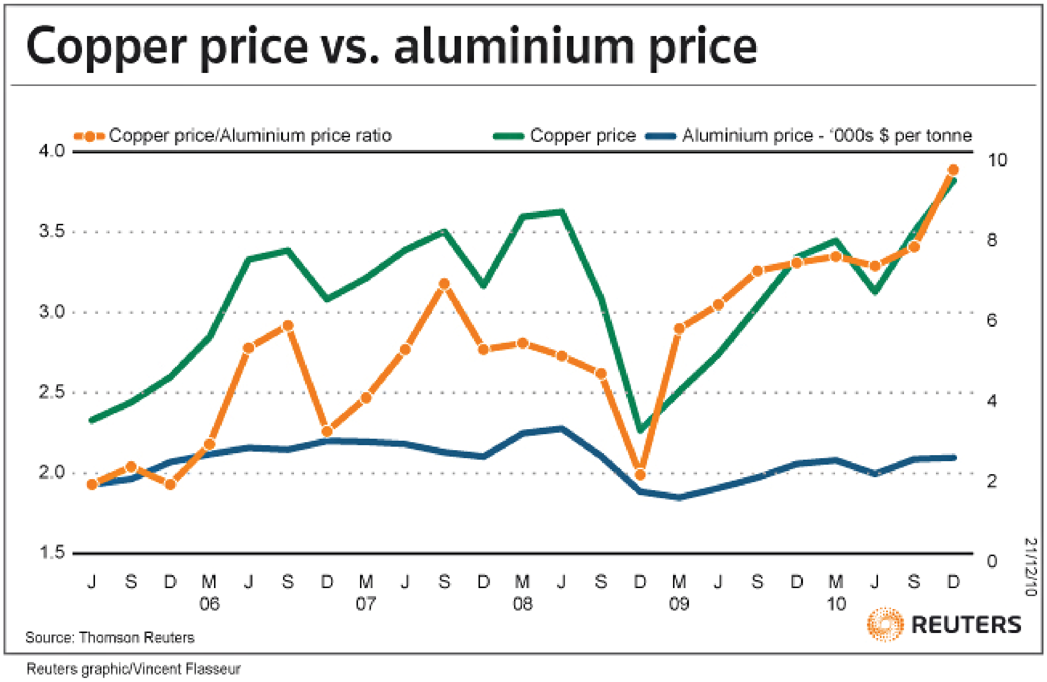

Figure 1: Copper and Aluminum prices from 2009 to 2011 (source: Reuters)

Because aluminum has a different value for the resistivity, ρ, a larger diameter wire is needed for aluminum to transport the same amount of current as copper.

$$csa = \pi * \frac{d^2}{4} = \rho * \frac{l*P}{V^2} => d = 2 * \sqrt{\frac{\rho*l*P}{\pi*V^2}}$$

In contrast to the costs of copper and aluminum, the ρ differential is only:

$$\Delta d = \sqrt{\frac{\rho\ aluminum}{\emptyset\rho\ copper}} \sim 1.24$$

$$\rho_{copper} = 0.0169\text{-}0.0175[\Omega * \frac{mm^2}{m}] \qquad \rho_{aluminum} = 0.0265[\Omega * \frac{mm^2}{m}]$$

Using this factor, aluminum costs are approximately half that of copper. In addition, copper has a higher density of 8.96 g/cm^3 compared to aluminum with only 2.7 g/cm^3. Even with the thicker aluminum wires there is a reduction of weight in a vehicle harness. The additional costs for processing aluminum wires and other technical difficulties are not recognized in this rough calculation.

INTEGRATING FLOW FOR 48V SYSTEM COMPONENTS AND ALUMINUM WIRES

BUILD 48V COMPONENTS INTO A 12V VEHICLE SYSTEM

The first step is to investigate replacing 12V system components (figure 2) with 48V components. This change will require updating existing wiring as well as adding new wiring using synthesis methods.

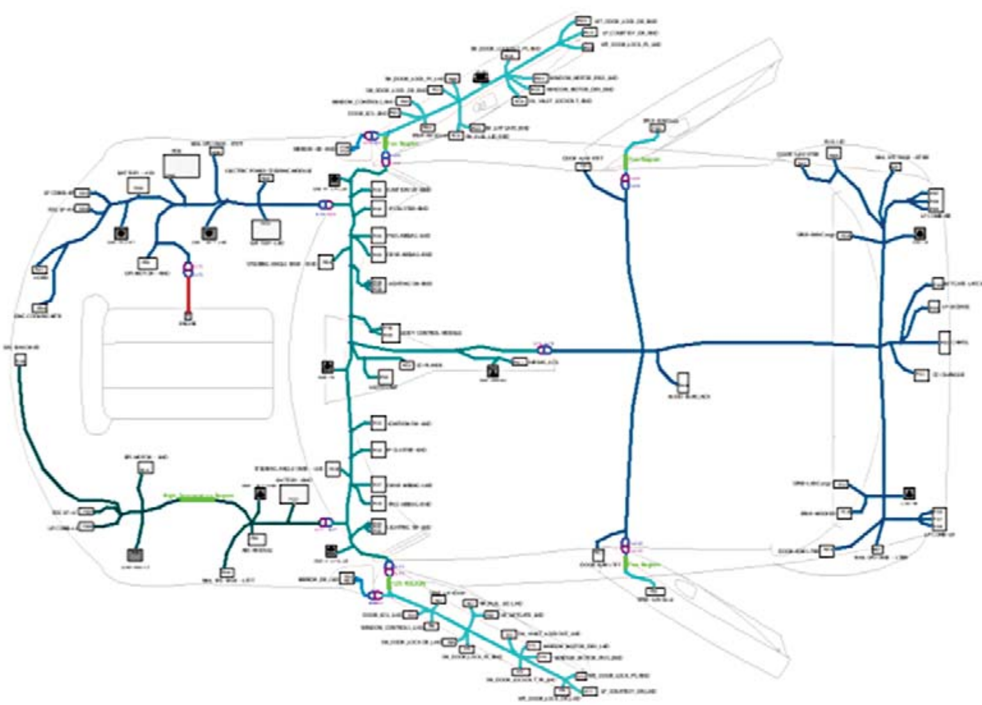

Figure 2: Example of a typical vehicle topology

In this example, we replace the power 12V-only system, the engine cooling, the antilock brakes and the electric power steering with 48V components.

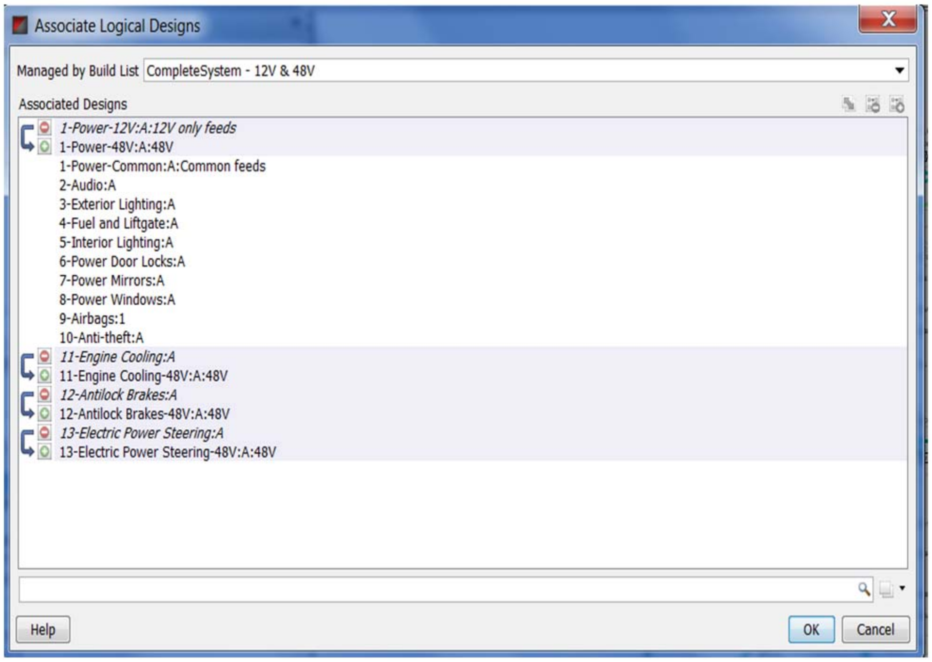

Figure 3: Replacement of 12V system components in the vehicle topology

The majority of the wiring could be reused, including most of the replaced vehicle systems. Only the new 48V devices not found in the 12V system need to be re-wired. In this example the wire count drops by six because of the six new 48V device fuses and grounds.

Automatic placement of the new devices could be done using rule-based methodology. For the new 48V grounds, ground paths are as short as possible.

After everything is placed, the wiring has to be updated. Using wiring synthesis to update the wiring is the fastest and most secure technique. This process eliminates looking over dozens of wiring diagrams to perform manual updates. Synthesis automatically creates these updates for all the wiring, based on best design practices, using rule definitions.

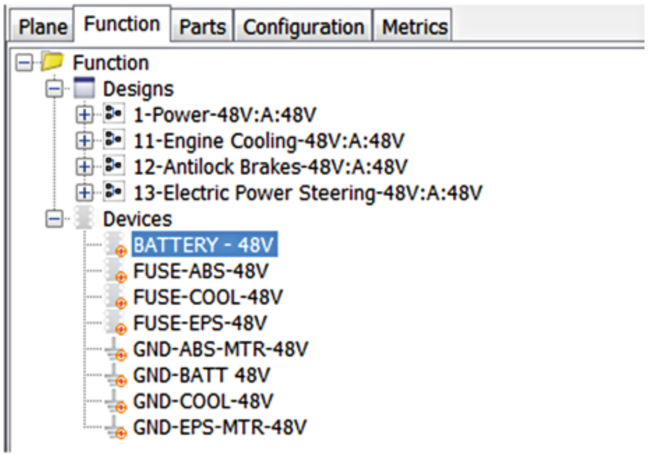

Figure 4: Unplaced 48V devices and grounds

After the new wiring, the wire count is increased by two in our example. This makes sense because the synthesis engine has to connect the six 48V fuses and grounds which had been 12V fuses and grounds. The only additional device to wire up is the 48V battery with one ground and one power wire.

VERIFICATION OF A MIXED VOLTAGE SYSTEM

Now the mixed voltage system has to be checked for any failures that may have been introduced by the replacements. To uncover these we need to employ failure mode analysis.

FMEA is a design tool used to systematically analyze potential component failures and identify the resultant effects on system operations[4]. During the FMEA test, every possible switch/input combination is tested on every single defined failure mode of every device and component of the mixed voltage system. This also means these failure modes must be defined up front. In the following two examples of a wire and a body control module, the implementation from Mentor Graphics software will be used to illustrate. The description of the body control module model of our example vehicle system will be the starting point.

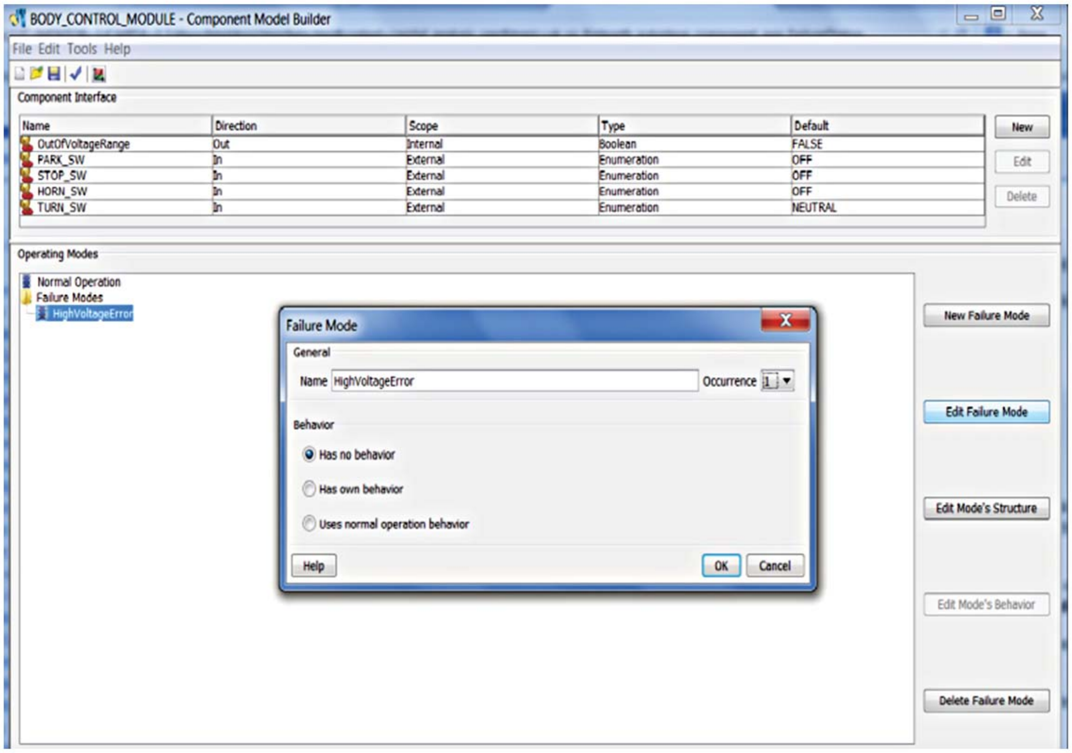

Figure 5: Body control module model and failure mode behavior

The model has two modes, one for normal operation and one for failure modes. For the body control module, there is only one failure mode: "HighVoltageError". In the failure mode window, the expected behavior is described as "Has no behavior". This means it does not have its own description, only the one in the "Edit Model's structure". This will be explained on the wire model. If "Has own behavior" is selected, "Uses normal operation behavior" would use the model of the normal operation. The occurrence value indicates how often this failure is likely to happen and is used in the calculation of Risk Priority Numbers (RPNs). The lower the number, the lower the chance of the failure occurring.

The model itself has four external inputs and one internal output. The external inputs could be control by the user or by analysis engines like the FMEA tool. Internal output will be used in this model only. Here this output will be controlled by the model of the normal operation.

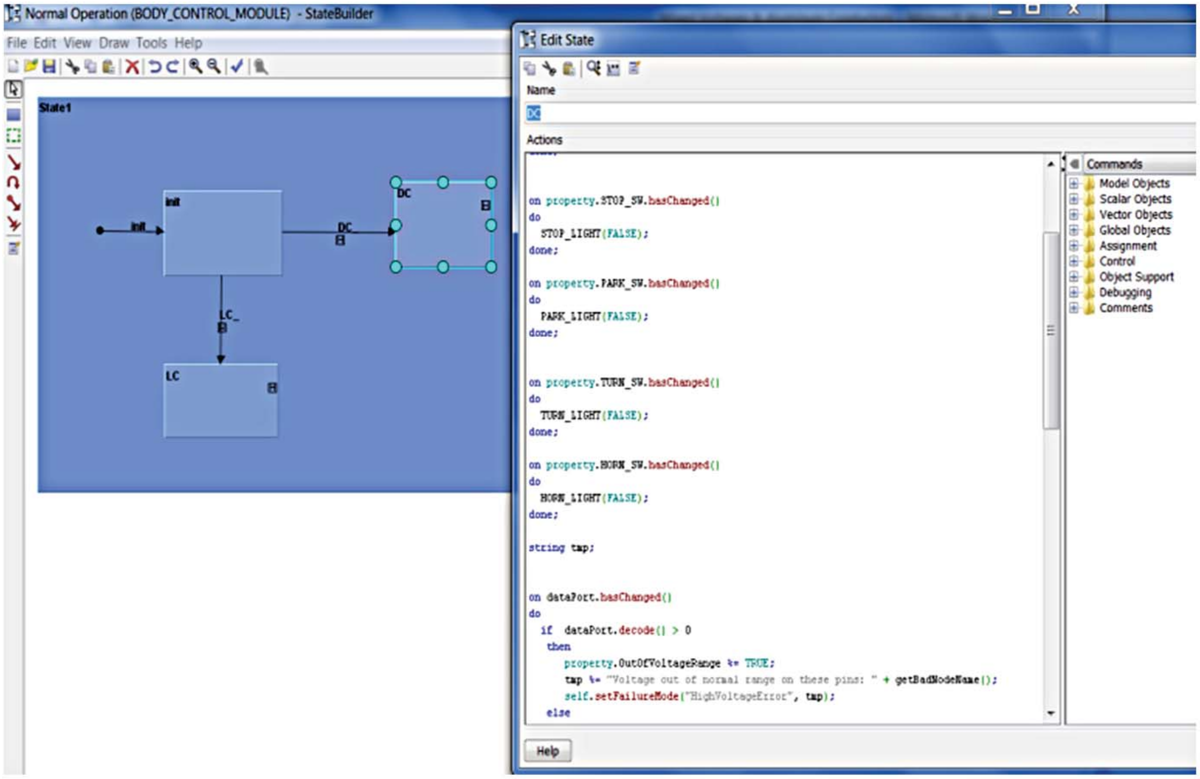

Figure 6: Model editor (state and text editor)

In normal operation, the body control module could run in two different modes: LC, or Logic only mode (only logic 0 and 1), or DC mode (numeric simulation). The models can be described with a state editor or with a proprietary language (see figure 5). This language is used within Dependency Expressions and State Machines to describe the behavior of a component in relation to any inputs. and within the Script Tool to way a script should perform an analysis of a design. In our example the “HighVoltageError” will be set to true if, during a numeric simulation, voltage is over 12V.

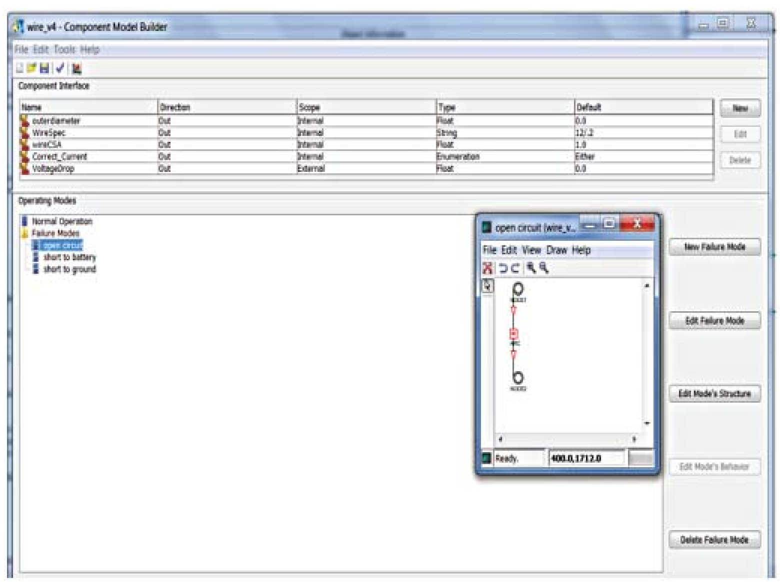

Figure 7: Wire model and structure model for an open circuit failure

The wire model is similar to the body control model, but has a different number of defined failure modes. For a wire, three failure models are defined. For an “open circuit” failure, the structure model is shown. In this case the resistance between the nodes is infinite. For the other failure modes it is a finite load.

With this information, the FMEA tool can begin. For each operational scenario single or double failures are injected for each selected component, or all components. The tool evaluates the effect of failures and calculates the RPN, defined as cost (of the event) multiplied by probability (of the event occurring) and detection (the probability that the event would not be detected before the user was aware of it)[5].

Once complete, the result is displayed as an FMEA report, in this case ordered by RPN.

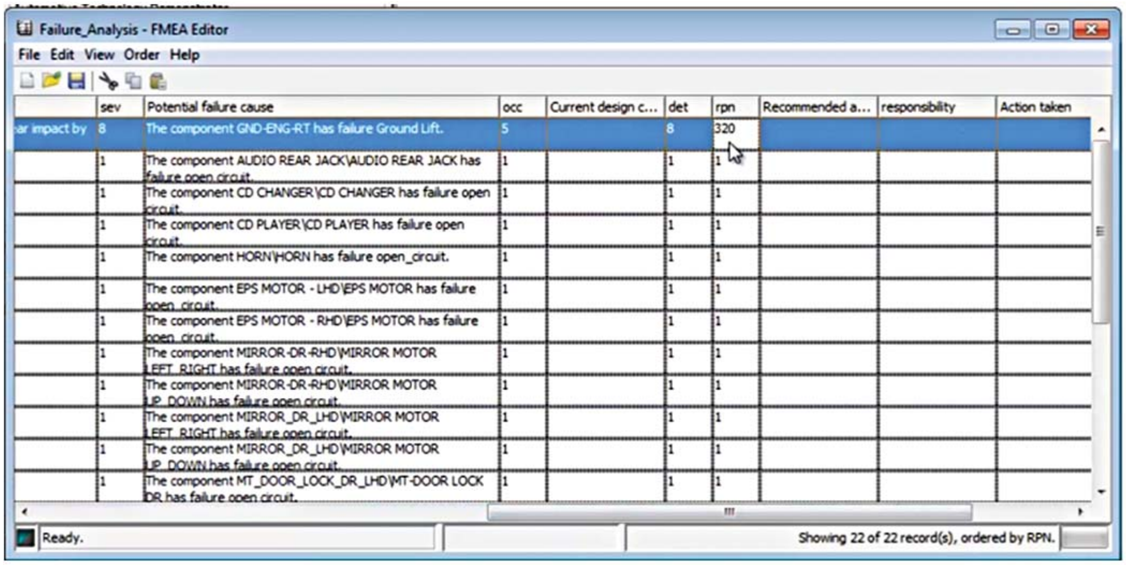

Figure 8: Parts of a FMEA report ordered by RPN

Now, you can see the failures in a platform view by displaying the associated record.

The user can view the expected, actual or differences result. Here, there is a failure due to a ground lift of the 48V which leads to an overvoltage at the body control module. This could be fixed with a separate ground for the 48V devices.

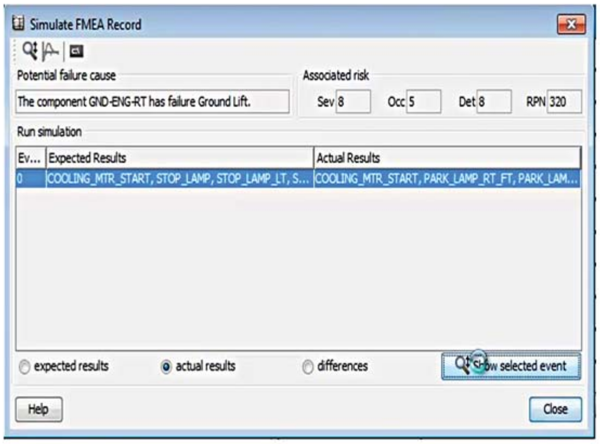

Figure 9: Context window to start the record on a failure

REPLACEMENT OF COPPER WITH ALUMINUM WIRES

In the next step, some copper conductors are replaced by aluminum ones. To execute this replacement, a rule will be put in place to give all conductors greater than or equal to 1.0 mm^2 CSA, assuming this is the smallest wire size for aluminum.

Also, a custom rule will be activated in a same way on harnesses to use copper only. This makes sense in high temperature areas like in the engine harness.

If we apply these rules to the topology, every wire with CSA equal or greater gets the property of aluminum except for the copper-only engine harnesses.

Next, the optimal wire CSA can be calculated and back annotated. For this, Mentor's SimStress tool will be used. During this test the tool finds the worst case operating condition (maximum current) for all components in the system and automatically calculates the optimum wire and fuse sizes.

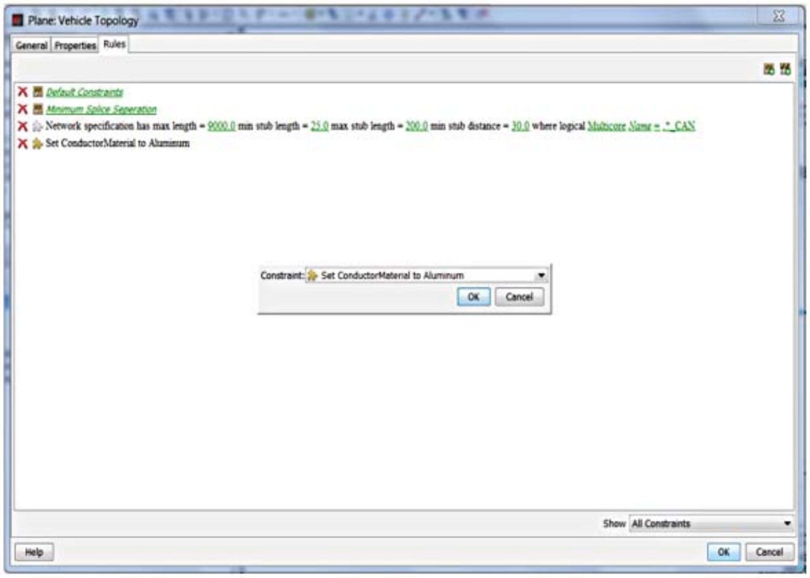

Figure 10: Context window to apply custom rule to the topology

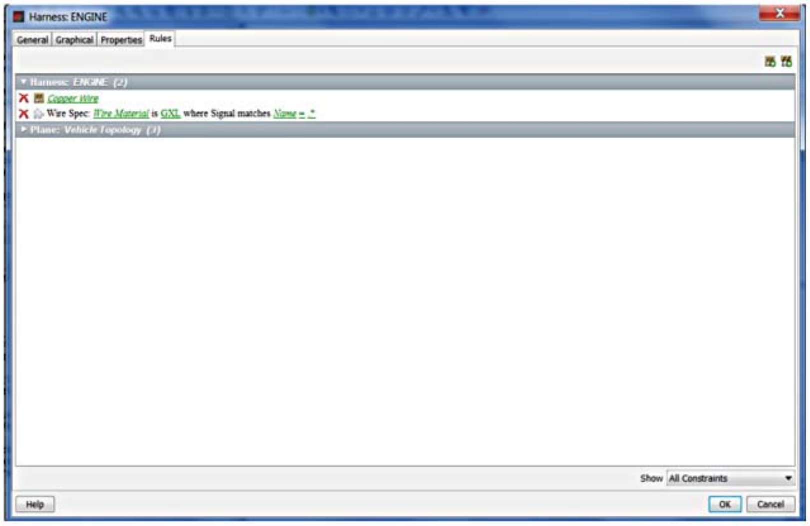

Figure 11: Context window to apply custom rule to the engine harness only

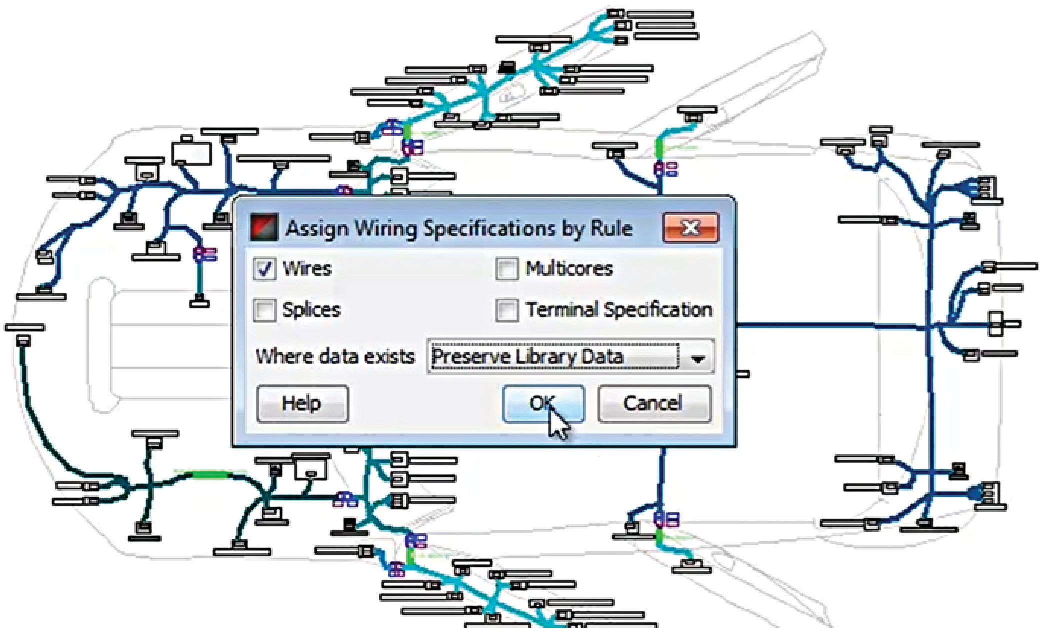

Figure 12: Apply rules to all wires in topology by preserving existing Library data

The tool sweeps through all operating conditions, extracting the worst-case load for each circuit, examining each wire against the worst-case load, examining if the fused wire is protected, suggesting wire sizes and fuse sizes, and reporting worst-case values and suggested component sizes.

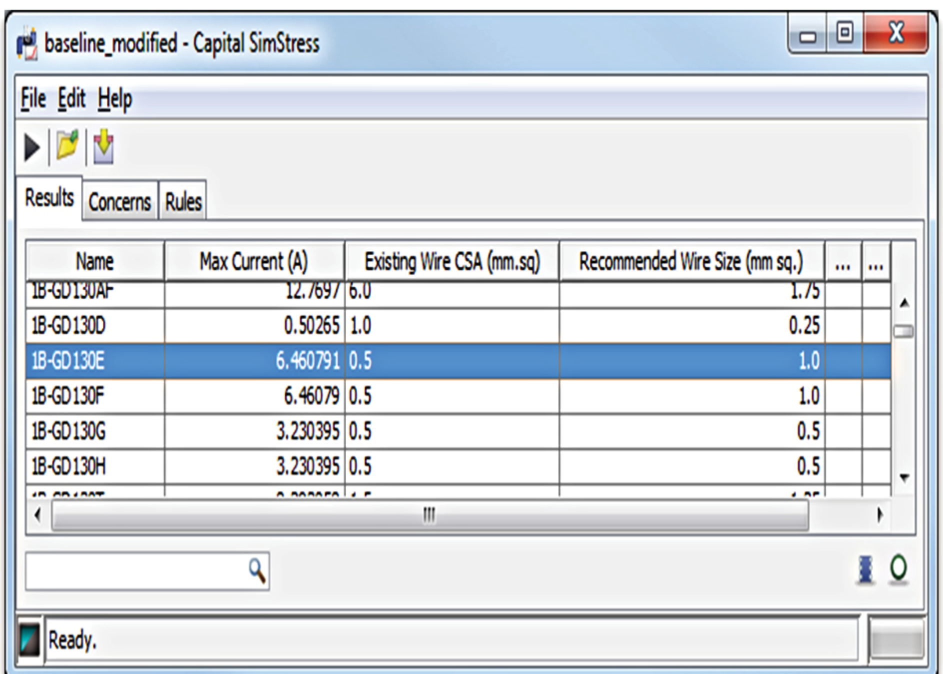

Figure 13: SimStress example report with worst-case values, actual wire CSA and recommended wire size.

Users can also customize the SimStress report. Using the report window users can back annotate the recommended wire and fuse sizes.

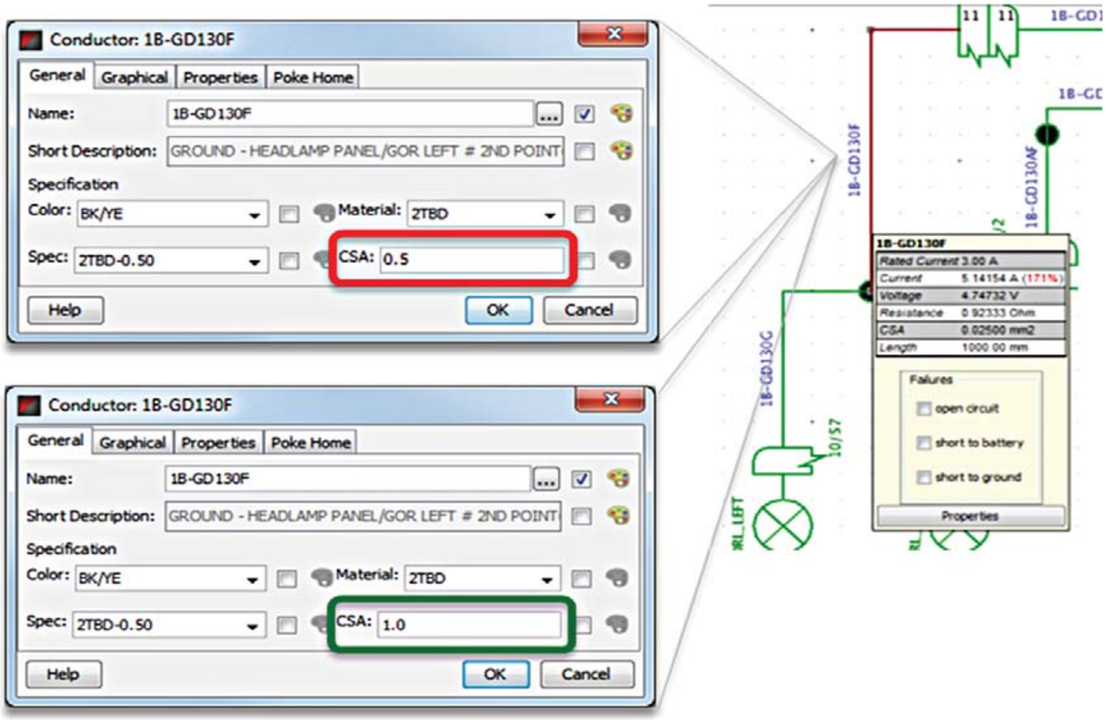

Figure 14: Example of back annotation of the recommended wire size (red old one, green recommended one)

To calculate the recommended CSA, the following formula is used

$$csa = \rho * \frac{l * P}{V^2}.$$

For ρ, the corresponding value for copper and aluminum must be inserted. The formula is part of the wire model written in SAINT. The recommended CSA shown in the result report of SimStress is generated by mapping the calculated values available wire sizes.

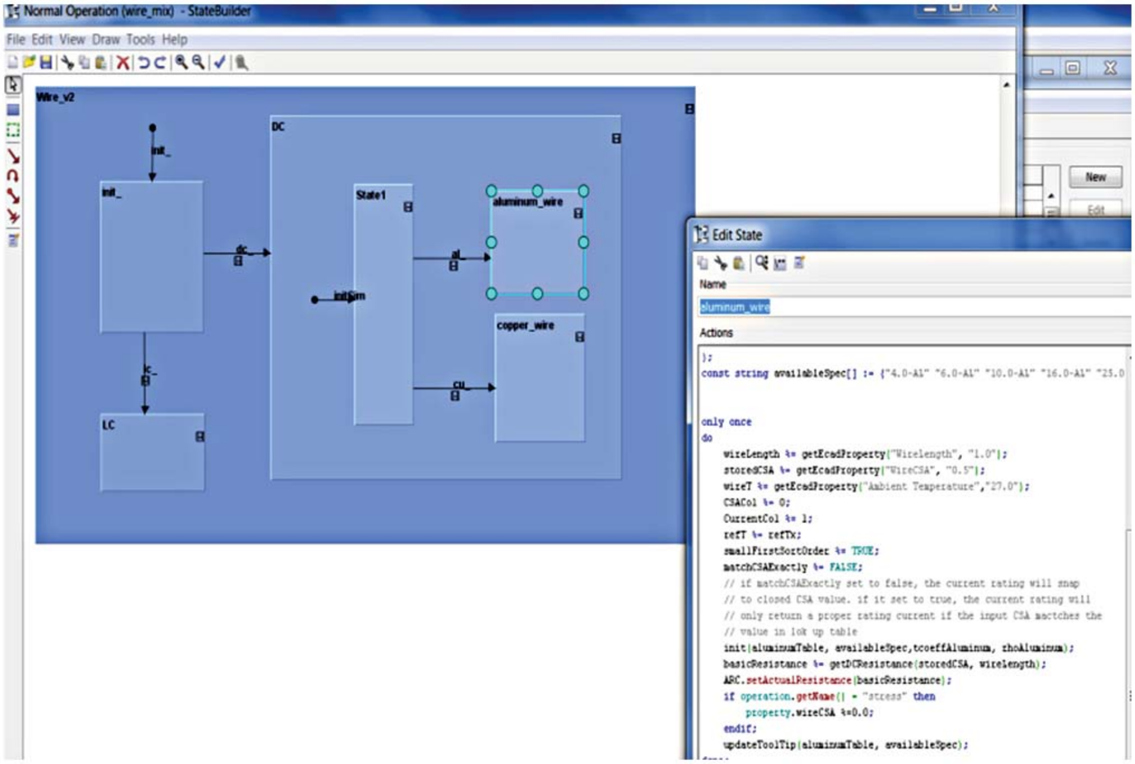

Figure 15: Wire model for simulation and wire sizing of copper and aluminum wires

EXAMINE THE RESULTS OF ALL RECOMMENDED CHANGES

It's necessary to understand the impact of these changes. A method and tool would be helpful to see the affect of each change. The first step is to determine what advantages a 48V/12V platform design has versus the pure 12V platform, in terms of both cost and weight. Studies can be run on the tool and the results examined. The 48V study, for example, has three scenarios pointing to three different platform designs.

For each study, the user can choose which metrics are relevant. Common metrics are cost and weight but it is easy to create other studies to measure business and engineering needs. Comparing the wire specifications of the 12V against the 48V platform in a spider diagram, we can see that the 48V platform has more small wires and fewer large wires.

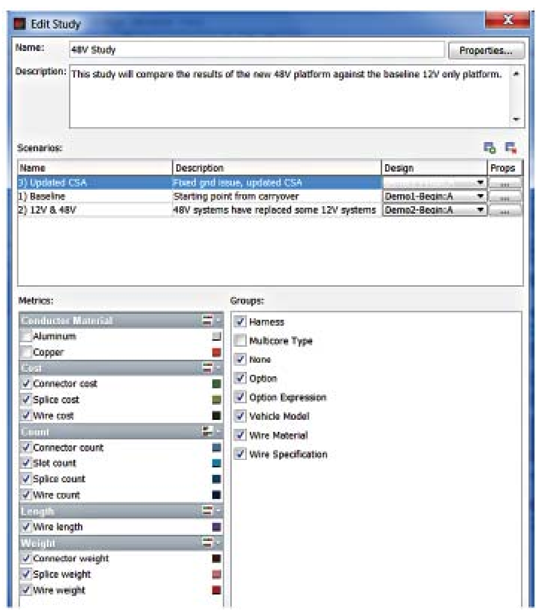

Figure 16: Configuration windows for studies

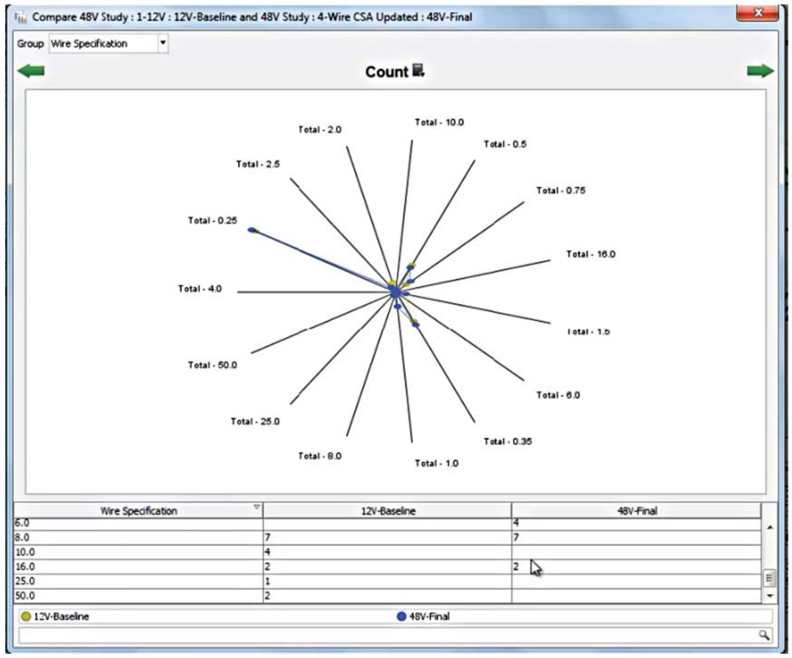

Figure 17: Spider diagram of wire specifications metric for 12V and 48V platform study

That makes sense because with increasing voltage, the current decreases for the same power, therefore smaller wires are acceptable. Cost is a critical metric. We can see that we have quite a bit of wire savings in this case.

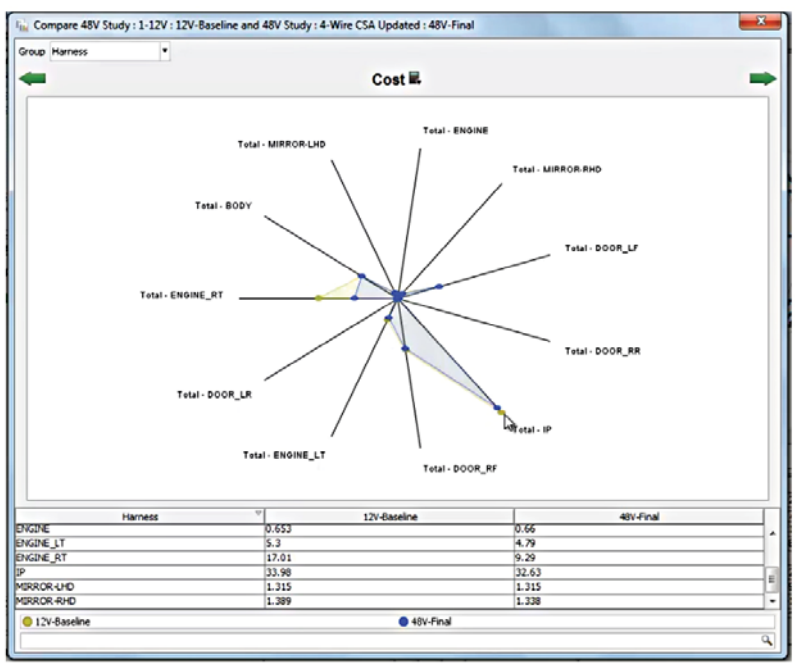

Figure 18: Spider diagram of cost metric for 12V and 48V platform study

The ENGINE_RT harness shows a significant savings because it also has the most high-power systems. We could approximate the same thing for weight (not shown).

Now, compare the copper platform to the mixed copper/aluminum platform.

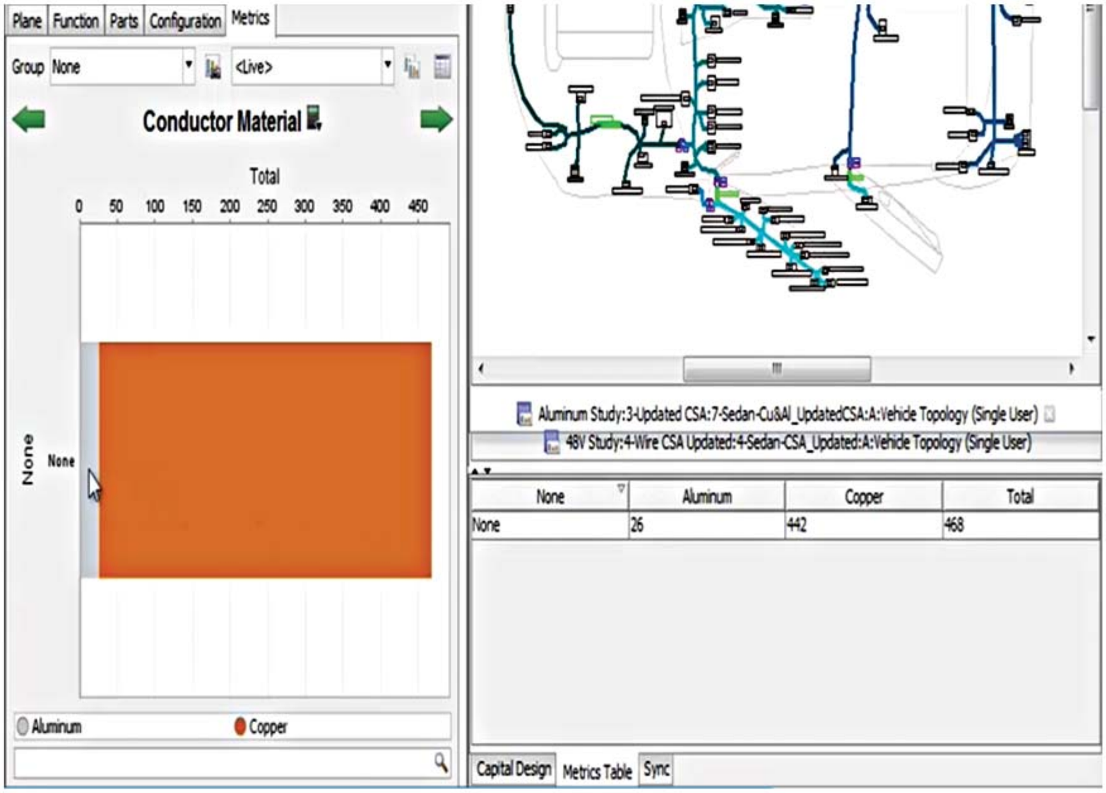

Figure 19: Conductor Material metric of aluminum study

Within the conductor material metric (figure 20) the number of aluminum and copper wires is displayed. These 26 aluminum wires were implemented based on the defined rules. You could also break down the numbers into the changed wire sizes.

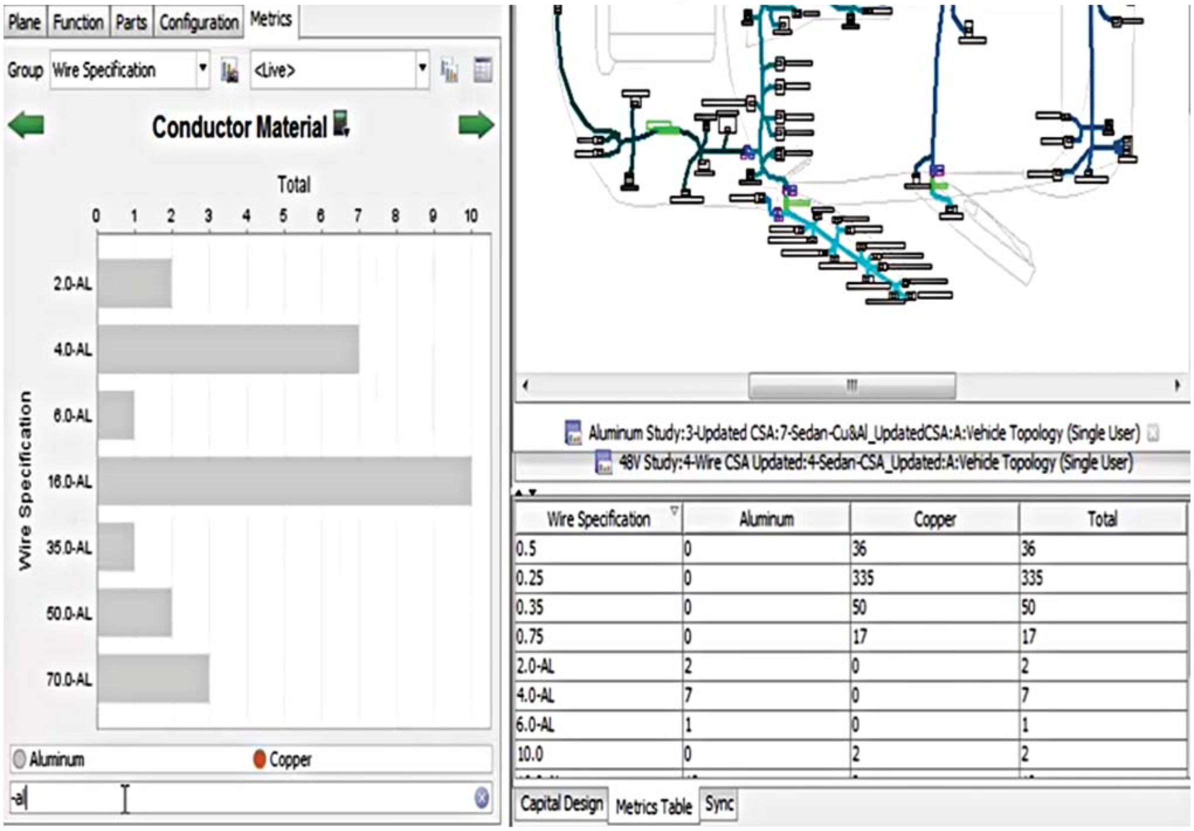

Figure 20: Conductor Material metric of aluminum study break down to wires sizes

Comparing the copper-only platform against the mixed material platform we see that our platform weight has decreased fairly significantly due to the wire weight reduction (figure 21). The wire costs also go down. This confirms our original hypothesis.

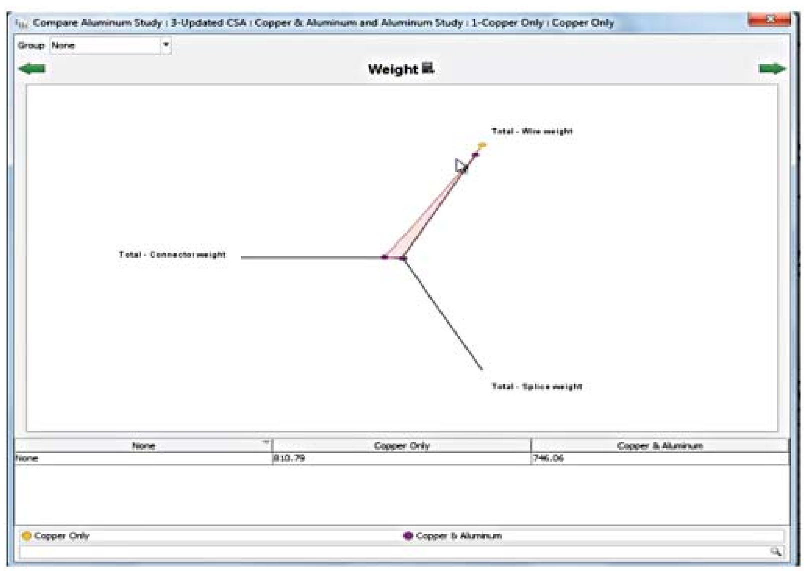

Figure 21: Spider diagram of weight metric for copper only and mixed material platform

The cost of the wire also decreases with aluminum.

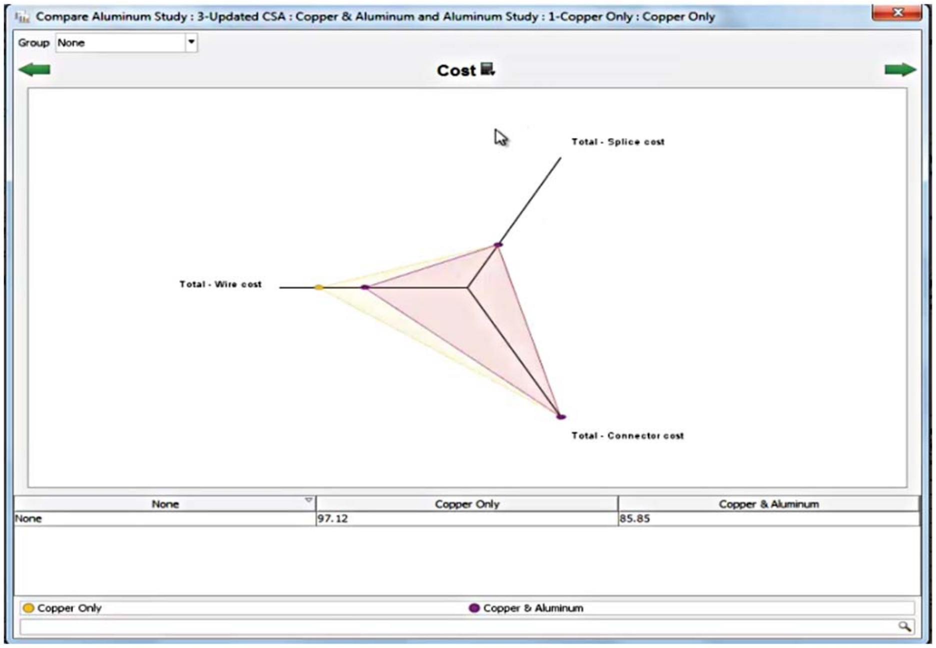

Figure 22: Spider diagram of cost metric for copper only and mixed material platform

If any attributes change in the future, it is a trivial task to adjust the metric and launch the comparison again. Data can also be grouped to examine the impacts of these changes on the harnesses.

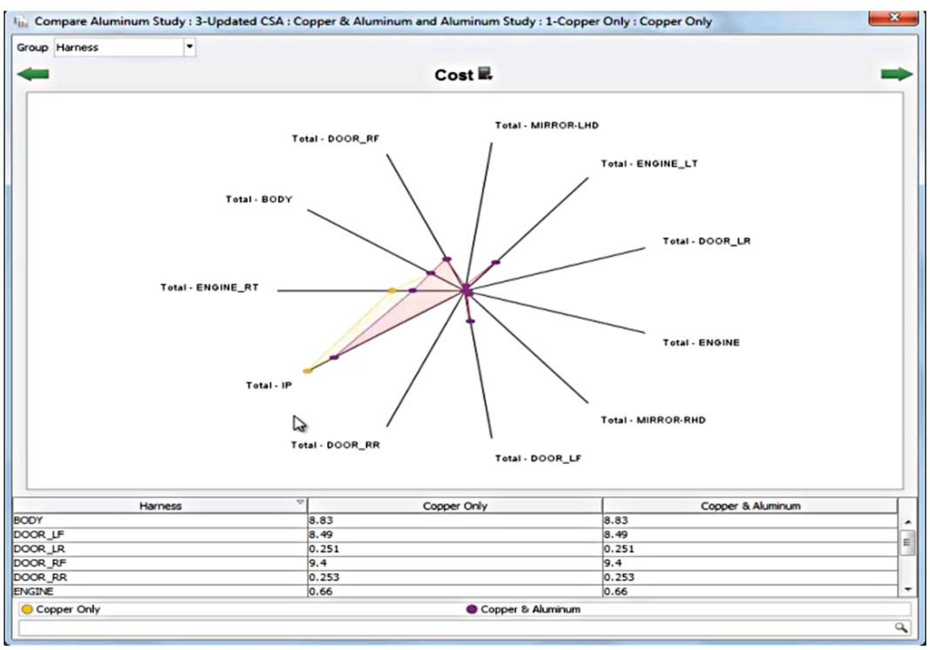

Figure 23: Spider diagram of cost metric for copper only and mixed material platform break down to the harnesses

Viewing and comparing metrics is a critical part of these studies. Users can watch the changes as the new technologies are implemented and compare the different scenarios. This could be done live and in a harness design environment.

SUMMARY/CONCLUSIONS

The paper investigates how a 48V harness could be implemented and verified in a vehicle platform to save cost and weight. Also a partial-replacement process of copper with aluminum was introduced. Various studies at the vehicle level were examined to highlight the value of the implemented technologies.

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